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THESIS

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METEOR BURST COMMUNICATIONS FOR THE
U.S. MARINE CORPS
EXPEDITIONARY FORCE

by

Bernal B. Allen

March 1989

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Meteor Burst Communications (MBC) is explored in relation to its usefulness to Marine Expeditionary Force Communications. A description of the physics and geometry of meteor trail propagation is presented. Communication techniques used to exploit the phenomenon are discussed. Current MBC circuits have operational ranges of 1200 miles without relay and maintain average data rates of 60 to 150 Bits per Second(BPS). MBC is primarily limited by the physics and geometry of the propagation medium and its usefulness is bounded by its slow data rate. Within these boundaries however, several significant uses of MBC are identified.

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METEOR BURST COMMUNICATIONS FOR THE U.S. MARINE CORPS EXPEDITIONARY FORCE

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN TELECOMMUNICATIONS SYSTEMS MANAGEMENT

from the

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ABSTRACT

Meteor Burst Communications (MBC) is explored in relation to its usefulness to Marine Expeditionary Force Communications. A description of the physics and geometry of meteor trail propagation is presented. Communication techniques used to exploit the phenomenon are discussed. Current MBC circuits have operational ranges of 1200 miles without relay and maintain average data rates of 60 to 150 Bits per Second(BPS). MBC is primarily limited by the physics and geometry of the propagation medium and its usefulness is bounded by its slow data rate. Within these boundaries however, several significant uses of MBC are identified.

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I. INTRODUCTION

The Earth is constantly bombarded by millions of particles (meteors) from outer space. As these particles pass through the earth's atmosphere, they leave trails of ionized gases. These ionized trails provide a path for the propagation of radio frequency energy. The use of meteor trails for communications has come to be known as Meteor Burst Communications (MBC). The "Burst" involves the transmission technique required to exploit the short time duration in which meteor trails exist.

MBC began to receive serious attention in the 1950's when it was viewed as a viable alternative to the long haul communication methods of the time, e.g., High Frequency (HF) radio, microwave radio, and cable. With the development of satellite communications in the early 1960's, interest in MBC diminished. Today, our growing concerns with both the vulnerability of satellite communications, and the availability of sufficient satellites to meet our needs, has once more made MBC an attractive, alternative method of long haul communications.

A. HISTORY OF MBC

Early work in MBC was conducted by the National Bureau of Standards and the Stanford Research Institute in the early 1950's. Both organizations had limited success, but confirmed that the sporadic, long distance propagation of radio waves in the Very High Frequency (VHF) spectrum could be attributed to meteor activity.[Ref. 1 p. 27-30]

The Canadian JANET system operated throughout most of the 1950's. Established by the Canadian Defense Research Board in 1952, JANET operated over communication paths of 900 to 1200 KM and achieved average data rates of 34 words per minute.[Ref. 2 : p. 1655] The National Bureau of Standards incorporated some of the techniques developed on the JANET system and conducted experiments over 628 and 1277 KM paths. These experiments pushed the average data rate to 30 Bits per Second (BPS), with a system Bit Error Rate (BER) of $3.5x10^{-3}$[Ref. 3 : p. 81].

In 1965 the COMET system was established by NATO's Supreme Headquarters Allied Powers Europe (SHAPE). The first operational military MBC system, COMET, connected stations in France, United Kingdom, Norway, West Germany, and Italy. The system could maintain, depending on meteor activity, two to eight, 60 WPM teletype circuits. Hourly data rates of 150 BPS were achieved.[Ref. 4 : p. 6-7,Ref. 1 : p. 35]

The SNOTEL system was built for the Department of Agriculture by Western Union. It started operations in 1977 under the management of the Soil Conservation Service (SCS). SNOTEL collects information on snowpack conditions in the Rocky Mountains. The information is critical to water management planning in the West. The system covers eleven western states with 511 remote MBC stations. The remote stations are located in harsh, inaccessible terrain. They are unmanned and solar powered. The remote stations are controlled by two master stations located in Boise, Idaho and Ogden, Utah. The master stations collect data from the remotes each morning, when meteor activity is the strongest. Each remote sends data collected over the previous 24 hours in a 200 bit message. The collection process averages 20 minutes for the entire system.[Ref. 5 : p. 75-77]

There are several MBC systems operating in Alaska, two of them are the Alaska Meteor Burst Communication System (AMBCS) and the USAF's Alaska Air Command MBC system. The AMBCS, operating since 1977, is used by several government agencies. The Bureau of Land Management uses it to communicate with its survey teams operating in the Alaska wilderness. The SCS uses it for the same purposes as the SNOTEL system. The Federal Aviation Administration (FAA) sends weather information over the AMBCS and employs it during search and rescue operations in remote areas.[Ref. 5 : p. 78-79] The USAF system is used to provide backup connections among the Regional Operations Control Center (ROCC) located at Elmendorf Air Base near Anchorage, and 13 Long Range Radar (LRR) sites located throughout Alaska. Primary communications for these USAF organizations is provided by the ALASCOM, satellite system. The ALASCOM system is vulnerable to jamming, however, because "part of its footprint extends over the Soviet Union, and therefore,... could not be relied on during a US-USSR crisis."[Ref. 6 : p. 0567] The MBC system sends radar "tracks" from the LRRs to the ROCC and has demonstrated the ability to carry enough data to maintain a real time radar display [Ref. 7 : p. 46]. The USAF system includes a limited voice capability, allowing the ROCC to control interceptor aircraft over the MBC system. Routine dialog between a controller at the ROCC and an intercept pilot is limited to a small set of commands. A voice synthesizer added to the aircraft, has a coded vocabulary large enough to handle most of these routine commands. When conducting an intercept, the controller types a command code into the MBC terminal, and the pilot hears the command in English. The pilot is limited to acknowledging receipt or non-receipt of the message.[Ref. 7, 6]

An example of a modern, integrated MBC network, is the North American Aerospace Defense Command (NORAD) network consisting of three master stations and 18 remote terminals. The network covers two thirds of the U.S. and is managed by the USAF's 25th Air Division, headquartered at McCord AFB, Washington.[Ref. 6 : p. 0568] The primary purpose of this MBC network is strategic reconstitution.

MBC is a mature technology. The abbreviated history offered above demonstrates that, not only are MBC applications possible for many communication situations, they are now being successfully employed.

B. THESIS ORGANIZATION

The intent of this thesis is to develop a MBC information base, adequate for the exploration of its applications to the United States Marine Corp's, Marine Expeditionary Force (MEF) communications. To that end, the thesis is organized into three basic parts. The first part, Sections II and III, focuses on the physics and geometry of meteor trail propagation and what communication parameters this path produces. Next, Section IV discusses techniques required to exploit the MBC phenomenon. Both link and network considerations will be discussed. From this base, the last part of the thesis will outline communication requirements of the MEF that could be provided by MBC. The thesis will conclude with an analysis of the advantages and disadvantages of MBC.

II. MBC GEOMETRY AND PHYSICS

A. METEOR PHENOMENON

Meteors are particles of matter from outer space. They are usually associated with remnants of comets, circling the sun in elliptical orbits similar to the Earth's. Every day hundreds of millions of them enter the Earth's atmosphere. If a meteor survives its passage through the atmosphere and lands on the Earth's surface, it is labeled a meteorite. A typical meteor is about 1 millimeter in diameter, the size of a grain of sand. Communication signals are not reflected from the particle itself but from the stream of ionization left by the meteor as it is heated and vaporized by friction produced when it falls through the atmosphere. Table 1 gives estimated distributions of meteors entering the Earth's atmosphere. Meteors with masses greater than 10^3 grams pass through the atmosphere and become meteorites. Meteors with masses less than 10^{-8} grams are micro-meteorites, and float down through the atmosphere, causing no ionization.[Ref. 8 : p. 119] Table 1 shows statistics for sporadic meteors, not those associated with meteor showers. Meteor showers will produce significant increases in meteor activity, but their short-lived nature makes them unproductive for general communications. Figure 1 shows a listing of the major meteor showers [Ref. 9 : p. 163].

The amount of meteor trails in the atmosphere varies with time of day and season of the year. The optimum time of day for meteor communications is usually in the morning, often around dawn. The tendency for meteor communications to be optimum in the morning is caused by two factors. First, as the Earth moves in its orbit around the sun its leading edge (the part of the world at dawn) is the first to encounter meteors and draws them into the atmosphere by gravitational attraction. Segments of the planet not at the leading edge are exposed to areas of space "swept clean" of meteors. Only new meteors with orbital speeds faster than the Earth's are available for these segments of the Earth. Meteors in the atmosphere at other times of the day have in effect, "caught up" with the Earth.[Ref. 10 : p. 15]

Table 1. DISTRIBUTION OF METEORS IN THE ATMOSPHERE

Mass (Grams)	Radius	Number of this mass or greater swept up daily	Electron line density
10^{4}	8 cm	10	-
10^{3}	4 cm	10^{2}	-
10^{2}	2 cm	10^{3}	-
10	0.8 cm	10^{4}	10^{18}
1	0.4 cm	10^{5}	10^{17}
10^{-1}	0.2 cm	10^{6}	10^{16}
10^{-2}	0.08 cm	10^{7}	10^{15}
10^{-3}	0.04 cm	10^{8}	10^{14}
10^{-4}	0.02 cm	10^{9}	10^{13}
10^{-5}	80 microns	10^{10}	10^{12}
10^{-6}	40 microns	10^{11}	10^{11}
10^{-7}	20 microns	10^{12}	10^{10}
10^{-8}	8 microns	?	?

A second advantage to early morning propagation is that when the leading edge of the earth attracts a meteor, the orbital velocity of the Earth is added to the velocity of the meteor. The increased velocity means more friction and more ionization when the meteor enters the atmosphere. Again, meteors that over take the Earth during other times of the day have their velocities cushioned by the forward motion of the Earth and thus the ionization is reduced.[Ref. 9 : p. 15-17]

These two advantages to early morning communications produce what is known as a "diurnal" variation. The diurnal variation has an order of magnitude of approximately 4:1. A typical variation is shown in Figure 2 [Ref. 11 : p. 1592].

Meteor trails in the atmosphere vary seasonally as well. This seasonal variation is due primarily to the changing tilt angle of the Earth. Figure 3 is a view of the Earth as seen from the apex of its way.[Ref. 2 : p. 1646] The Northern Hemisphere is tilted away from the apex in the winter and towards it in summer. More meteors are observed in summer than in winter. Figure 4 shows the Northern Hemisphere seasonal variation

Major (and Minor) Meteor Showers				
Shower	*Date Range*	*Peak Date*	*Time Above Quarter Max*	*Velocity KM/Sec*
Quadrantids	Jan 1-6	Jan 3	14 hours	41.5
(Lyrids)	Apr 18-25	Apr 21	2.3 days	47.6
Eta Aquarids	Apr 21-May 12	May 4 5	3 days	65.5
Arietids	May 29-Jun 19	Jun 7	?	37.0
Perseids	Jul 23-Aug 20	Aug 12	4.6 days	59.4
Orionids	Oct 2-Nov 7	Oct 20	2 days	66.4
(Taurids)	Oct 20-Nov 20	Nov 3 4	?	28-30
(Leonids)	Nov 14-20	Nov 17	4 days	70.7
Geminids	Dec 4-16	Dec 13	2.6 days	34.4
(Ursids)	Dec 17-24	Dec 22	2.2 days	33.4

Figure 1. Major Meteor Showers

with the effects of meteor showers removed [Ref. 8 : p. 121]. Seasonal effects will be opposite in the Southern Hemisphere.

The daily and seasonal variations in meteor activity change in relation to location on the globe. The seasonal variations will be more pronounced at higher latitudes than at the equator. This is because the Earth's tilt angle is more pronounced at the poles. Conversely, the daily variation will be stronger at the equator because the Earth's diameter is larger there and thus its rotational speed will be greater.

B. FORMATION OF METEOR TRAILS

When a meteor enters the Earth's atmosphere it encounters air molecules. The collision between the meteor and the air molecules produces heat which evaporates atoms from the meteor. These atoms are boiled off the meteor with velocities substantially equal to the meteor. Collisions between these high velocity atoms and the surrounding air results in additional heat, light, and ionization. Thus a meteor trail is formed. The electron line density in the trail is proportional to the mass of the meteor. [Ref. 8 : p.121]

The Earth's atmosphere achieves the relative densities necessary to produce meteor ionizations at heights below 120 KM. Above this height, collisions with air molecules are not frequent enough to be of significance. By the time that most meteors reach heights of 80 KM above the Earth, all of their mass has been evaporated. The meteor region is then considered to be 80 to 120 KM above the surface of the Earth. Some

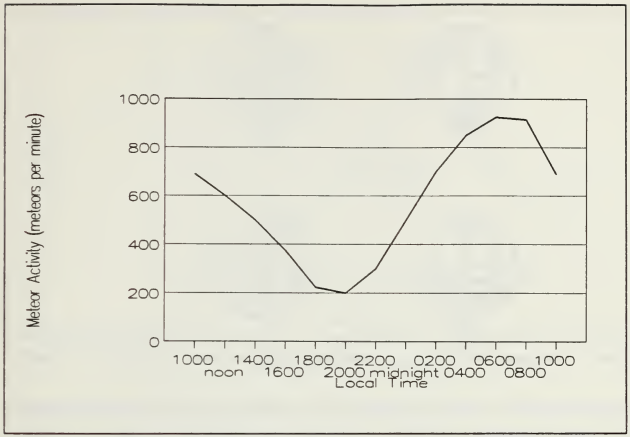


Figure 2. Diurnal Variation of Meteor Arrivals

variations in this region will occur due to variations in the meteors. Meteors with higher velocities will produce more evaporation earlier and will have higher trails. Meteors with more mass will produce maximum trial ionization at lower heights. [Ref. 8 : p. 121]

The lengths of the ionized trails are dependent on the mass of the meteor and the angle in which it enters the atmosphere. Trails can extend up to 50 KM but the average length is 15 KM. The general definition of trail length measures from the head of the trail to a point with a given threshold line density.

The initial radius of the meteor trail has been measured by photography and radio measurements. The initial radii are from 0 to 1.2 M with an average value of 0.65 M for photographic measurements and 0.55 to 4.35 M for radio measurements.[Ref. 8 : p. 121]

After the initial radius has been formed, meteor trails expand by diffusion. As the trail expands, the radial distribution of material in the trail is approximately Gaussian. The approximate radius of the trail after time T is $(4Dt + r_o^2)^{\frac{1}{2}}$ where D is the diffusion coefficient of the atmosphere and r_o is the initial radius of the trail. D varies from 1

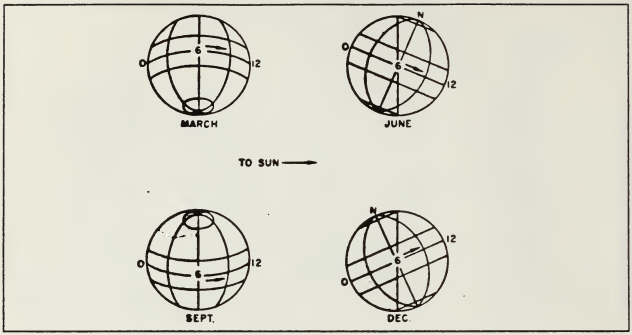


Figure 3. Seasonal Tilt of Earth as Viewed From Apex

M/sec at 85 KM to 140 M/sec at heights of 115 KM. After one second, trails will have radii of 2 to 20 M. [Ref. 8 : p. 122.]

As the trails expand, their value as radio reflectors diminish. The duration of a meteor trail as a communication path is dependent on the means used to detect it. Most trails used in radio communications result from small dust sized meteors; these last for only fractions of a second. Larger sized meteors produce more densely ionized trails. Durations of one minute or more are observed several times a day.

The presence of wind in the meteor region adds additional complications to meteor trail duration. When initially formed, meteor trails are relatively straight, but wind shear rapidly distorts them. The wind shear will not greatly effect trails that have short durations, but the longer lived trails produced by large meteors are vulnerable to this effect. Not only will high altitude winds diminish the durations of larger meteor trails but portions of the trails can be blown into positions that will created communication paths that the original meteor trail would not support.

C. METEOR TRAIL ELECTRON DENSITIES

When considering the ability of meteor trails to reflect radio energy it is convenient to divide the trails into two classes, underdense trails and overdense trails. In underdense trails the electron line density is low enough that the radio energy passes

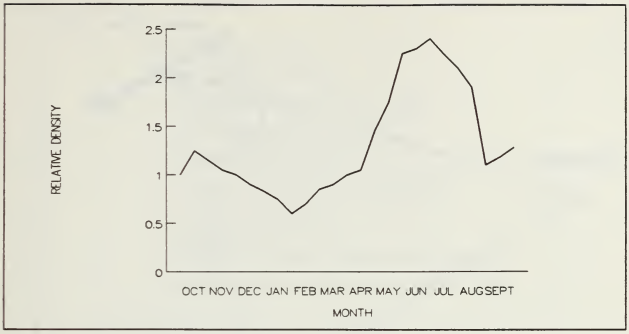


Figure 4. Seasonal Variation of Meteor Activity

through the trail and only a portion of it is forward scattered. The trail can be considered an array of independent scatters.[Ref. 8 : p. 122] Meteor trails with fewer than 10^{14} electrons per meter are considered underdense.

When the trail's electron line density is sufficient to block complete penetration by the incident wave of the radio energy, the trail is considered overdense. Radio propagation from these overdense trails is more easily conceived as reflection from a cylindrical surface vice the scattering that occurs with underdense trails. Overdense trails have more than 10^{14} electrons per meter [Ref. 2 : p. 1646].

The distribution of underdense trails to overdense trails is about three to one. The underdense trails have durations of about one second or less, while overdense trails last for longer periods of time [Ref. 8 : p. 124].

D. GEOMETRY OF METEOR TRAILS

The geometry of forward scattering of radio waves from meteor trails is represented by Figure 5 [Ref. 2 : p. 1646].

The geometric relationship between a radio transmitter, a remotely located radio receiver, and a meteor trail involves two planes. The first plane is the propagation plane formed by the transmitter, the meteor trail, and the receiver. ϕ is one half the angle of the triangle's apex. The second plane is formed by the meteor trail. β is the angle of

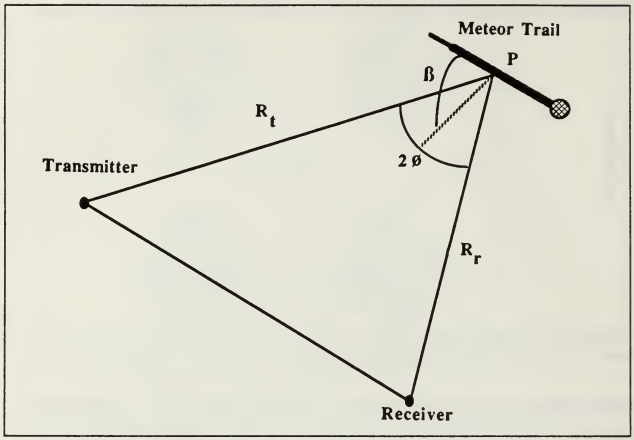


Figure 5. Geometry of Meteor Trails

the meteor trail relative to the first plane. R_t and R_r measure the distance from the transmitter and receiver to the meteor trail. Each meteor trail represents a unique set of parameters to this geometry. The distances and angles that describe the geometric relationship between the transmitter, receiver and meteor trail will have a significant impact on how much radio energy will be received and for what durations.[Ref. 2 : p. 1646]

E. TRANSMISSION EQUATIONS

Using the trail geometry listed above the transmission equations for a radio signal reflected by a meteor trail have been derived as follows. For underdense trails the equation is:

$$P_r(t) = \frac{P_T G_R G_T \lambda^3 r_e^2 q^2 \sin^2\alpha \exp\left[-\frac{8\pi^2 r_o^2}{\lambda^2 \sec^2\phi}\right]}{16\pi^2 R_T R_R (R_T + R_R)(1 - \cos^2\beta \sin^2\phi)} \exp\left[-\frac{32\pi^2 D}{\lambda^2 \sec^2\phi} t\right] \qquad (II.1)$$

[Ref. 2 : p. 0577]

Where

P_T	The transmitter power
G_R	The receiver antenna gain
G_T	The transmitter antenna gain
λ	The carrier wavelength
r_e	The radius of the electron
α	The angle between R_T and the electron field vector at the meteor trail
r_o	The initial radius of the trail
ϕ	The angle of reflection of the transmitted wave
β	The angle between the propagation plane and the meteor trail
R_T	The distance from the transmitter to the trail
R_R	The distance from the receiver to the trail
D	The diffusion coefficient of the atmosphere
q	The electron line density of the trail

The transmission equation yields a time varying received signal power. The $\sin^2\alpha$ term is a loss that accounts for the change in E-field polarization caused by the reflection off the meteor trail. This is mostly a function of Faraday rotation.[Ref. 12 : p. 4-6] The terms in the denominator of the main equation account for both the propagation dispersion of the transmitted energy up to the trail and down to the receiver, and the amount of the trail that is in the principal Fresnel zone of the transmitter.[Ref. 8 : p. 123] The exponential term controls the timing of the fade of the signal. The power received is proportional to λ^3 and q^2. The duration of the signal is proportional to λ^2. The signal from a typical underdense signal is shown in Figure 6. It has a relatively large initial value and then experiences rapid exponential decay.[Ref. 13 : p. 1702] Underdense trails produce very rapid signal fades; signal fades as high as 500 dB/second occur although 200 dB/second are more normal.

For overdense trails the transmission equation is given as:

$$P_r(t) = \frac{P_T G_T G_R \lambda^2 \sin^2\alpha}{32\pi^2 R_T R_R (R_T + R_R)(1 - \cos^2\beta \sin^2\phi)} \left[\frac{4Dt}{\sec^2\phi} \ln\left(\frac{r_e q \lambda^2 \sec^2\phi}{4\pi^2 Dt} \right) \right]^{\frac{1}{2}} \quad (II.2)$$

[Ref. 8 : p. 124]

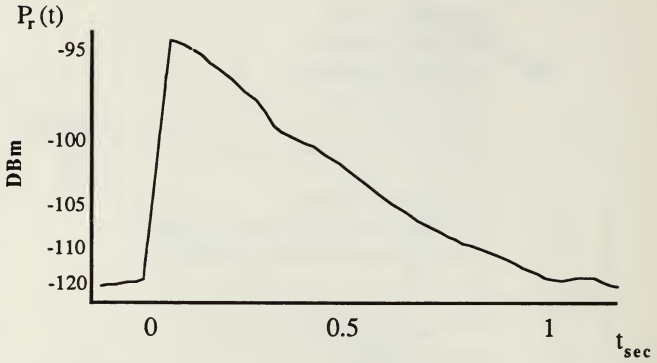


Figure 6. Typical Underdense Signal

For overdense trails the assumption is that the incident wave from the transmitter penetrates the trail until it reaches electron densities high enough to reflect it. The model used is of an expanding cylindrical reflector of radius r_e. Eventually the trail will expand to the point that electron densities can no longer support the reflection and then the underdense pattern of scattering is applicable.[Ref. 8 : p. 124] The overdense trails produce signals that behave more like the one pictured in Figure 7. A slower rise in received signal is experience followed by a period of sustained signal levels, finishing with the exponential decay experienced with underdense trails. The ideal received signal would have a smooth, unbroken transition of growth to decay, but due to the longer durations of overdense trails, actual received signals usually exhibit jagged forms because of the wind shear phenomenon discussed previously. The parameters of the overdense equation remain the same as the underdense. The received power is still proportional to λ^3 but now varies as the $\sqrt{q}$ vice q^2 for the underdense trail.

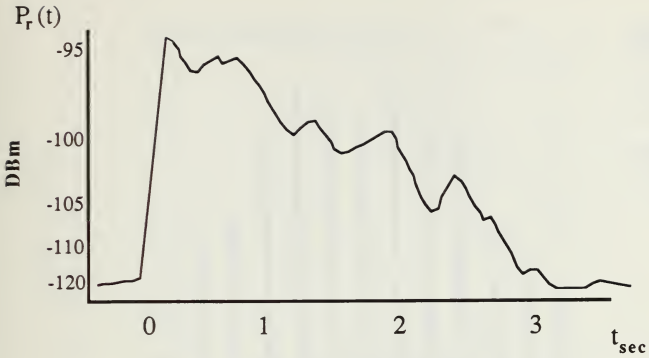


Figure 7. Typical Overdense Signal

F. CONSEQUENCES OF METEOR TRAIL PROPAGATION PATHS

The nature of meteor trails described above present several consequences to their use for communications. Among the most important communications aspects presented by meteor trails are:

- The random nature of the communication path;
- The time varying signals produced by the path; and
- The fact that each meteor trail describes a unique set of geometry between a transmitter and receiver.

Random nature. Meteors usable for communications arrive with random rates. A relevant statistic is the waiting time required for the next usable meteor trail. Waiting times follow a Poisson distribution. The fundamental Poisson equation is: [Ref. 14 : p. 17]

$$P = 1 - e^{-Mt} \qquad (II.3)$$

Where, P = Probability of a meteor occurrence in time t,

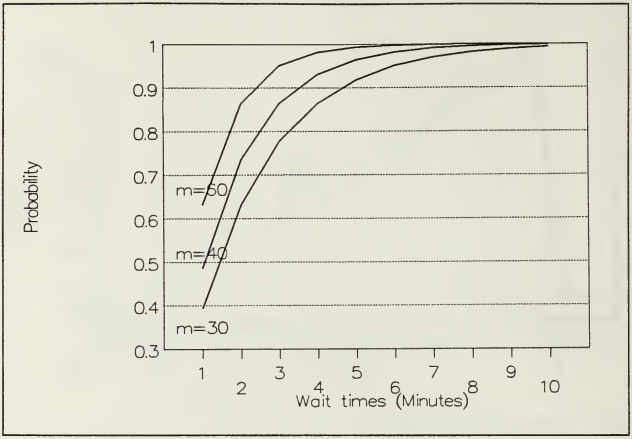


Figure 8. Poisson Distribution of Waiting Times

M = The meteor density or number of burst per hour

t = Time in hours

If time t is given in minutes the expression becomes:

$$P = 1 - e^{\frac{-Mt}{60}} \qquad (II.4)$$

Through operational tests, measurements of usable meteor paths per hour can be obtained to provide estimates for M. With this data, probable waiting times can be established. A family of curves for a set of meteor densities is given in figure 8.

An example of meteor trail densities, measured from operational tests comes from a 1260 KM research link operated by the USAF. The link in Greenland was between Sondrestrom AB and Thule AB. It operated continuously during the research period. Figure 9 shows the average rates recorded on the link for the month of February 1985. Meteor trails were recorded when the Received Signal Level (RSL) exceeded -110 DBM. [Ref. 15 : p. 3-2]

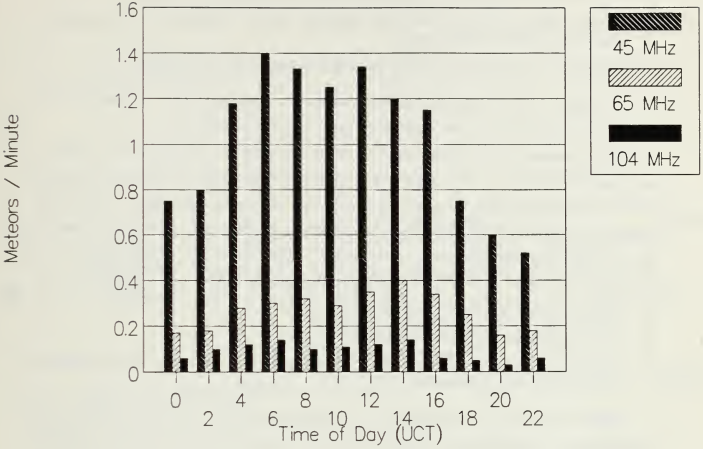


Figure 9. Meteor Arrival Rates by Frequency

Several points of interest should be noted with the data presented in Figure 9. The first is the frequency dependence of the trails. Significantly more trails are recorded at 45 MHz than at 104 MHz. Next, as discussed above and shown in Figure 3, meteor activity is generally low in February, especially in the higher latitudes where this data was taken. Finally, while a diurnal variation is present in the data, it is certainly not close to the 4:1 relationship that is expected. This lack of a sharp difference between dawn and dusk meteor activity can be attributed to the polar location where the recordings were made. As discussed earlier, the diurnal variations will be less at the poles and greatest at the equator.

Time varying. Meteor trails provided a communication path that is time varying. In order to exploit this time varying path, communication systems must:

- Detect when a path exists between the transmitter and receiver;

- Start and regulate the transmission of information sent by the transmitter;
- Push as much information through the path as possible when it exists;
- Detect when the path has faded to an unusable level and terminate the transmission when that level is reached; and
- Store data for transmission when no communications path is present.

In simplest terms a meteor communications system maintains operations that follows the cycle of "path open, send data/ path closed, store data."

Unique geometry. The communication circuit described by a transmitter, a receiver, and a meteor trail has a very specific set of angles and distances. It is unlikely that a third station could match the same geometry with out being very close to either the transmitter or receiver. Another way to describe this phenomenon is to say that meteor burst systems have small physical "foot prints." The uniqueness of the meteor trail, communication circuit provides several very useful consequences:

- MBC systems are difficult to intercept;
- MBC systems are difficult to jam; and
- Meteor trails provide a natural means of Time Division Multiple Access (TDMA) for communication networks.

Figure 10 shows the percentage of information that would be available for interception on a 1000 KM link. [Ref. 2 : p. 1656] Meteor trails present reciprocal paths relative to transmitting and receiving, so this same figure could also illustrate the effectiveness of a hostile jammer. The actual effectiveness of an intercept station or jammer would also be diminished by the random nature of the meteor arrivals times. [Ref. 16 : p. 71]

The small "foot print" of MBC systems will also allow stations, that are adequately separated, to use the same frequencies with little interference. The phenomenon can be used to automatically apportion access time among several stations on a MBC network. This provides a natural means of TDMA.

The consequences of the meteor trail geometry and physics must be exploited in order to achieve effective communications. Section III discusses the communication parameters that result from meteor trail propagation. Section IV continues with a review of several configuration issues in MBC system design. Subsequent sections apply this information to specific applications for Marine Expeditionary Force communications.

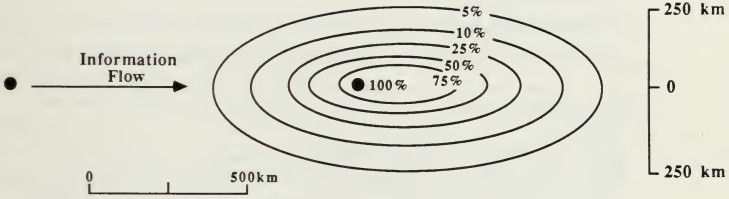


Figure 10. Information Available to Interceptor in Vicinity of Meteor Burst System

III. MBC COMMUNICATION PARAMETERS

The physics and geometry of meteor trail propagation described in Section II, yield certain distinct communication parameters for MBC circuits. A general review of the more important communication parameters is the focus of this section. The impact of meteor trail propagation on the following communication areas will be discussed:

- Radio Frequency;
- Transmitter Output Power;
- Antenna Configuration; and
- Communication Distance.

Both empirical and theoretically derived information will be applied. The intent is to develop an understanding of the basic capabilities and limitations relevant to communications by meteor trail propagation.

A. RADIO FREQUENCY CONSIDERATIONS

MBC has been employed on frequencies from 25 through 220 MHz.[Ref. 12 : p. 4-21] On frequencies below 25 MHz other forms of propagation, such as High Frequency (HF) sky wave, assume the primary role. The optimal frequency range for MBC is considered to be in the 30 to 50 MHz range. This is in the lower region of the Very High Frequency (VHF) band. As described in Equation (II.1), the received signal amplitude from underdense trails is proportional to λ^3, i.e. $\frac{1}{f}^3$. The time duration of the received signal is proportional to $\frac{1}{f}^2$. These two factors cause message waiting times to increase sharply at the higher VHF frequencies.[Ref. 14 : p. 3] Figure 9 is a good example of this phenomenon; there is a significant reduction in meteor arrival rates seen at 104 MHz as compared to 45 MHz.

Another frequency issue is the ability of a single meteor trail to simultaneously support communications on two frequencies while allowing enough separation to permit the adjacent operation of a transmitter and receiver. This "reciprocal propagation condition" was established in 1953 during tests between Ottawa and Port Arthur, Canada.[Ref. 2 : p. 1643] From these tests it was established that a single trail could support frequency separations of up to one MHz. A one MHz separation is sufficient for most MBC applications. As will be discussed in Section IV, most MBC systems operate with instantaneous data rates that range between 300 BPS and 32 kBPS. The

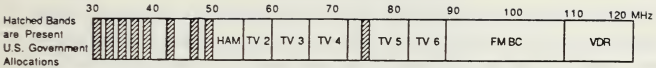


Figure 11. CONUS Frequency Allocations

half power bandwidth at 32 kBPS is 32 KHz for Binary Phase Shift Keying (BPSK) and 64 KHz for Quadrature Phase Shift Keying (QPSK) well within the one MHz reciprocal propagation condition.

Frequency availability is an important issue. The frequency spectrum is very crowded where MBC systems operate. Figure 11 shows how the lower VHF frequencies have been allocated to communication services in the continental United States (CONUS).[Ref. 12 : p. 4-25] The National Telecommunication and Information Administration (NTIA) controls frequency assignments for government users in the United States. NTIA has not considered permanent frequency allocations for MBC [Ref. 12 : p. 4-24]. The allocations shown in Figure 11 include eight sub-bands between 30 and 50 MHz and one at 75 MHz; one amateur radio (HAM) band (50 to 54 MHz), five television channels, the commercial FM broadcast band (88 to 108 MHz), and a navigation (VDR) band (108 to 120 MHz). Traditionally, the amateur radio bands become available for use during national emergencies. Most military radios operating at these frequencies tune from 30 to 75.95 MHz.

B. TRANSMITTER OUTPUT POWER

As a general rule, the more transmitter power that is used on a MBC circuit, the more successful that circuit will be. Both Equations (II.1) and (II.2) indicate that received signal power is directly proportional to the transmitted signal power. It has been shown experimentally that MBC system's information throughput is proportional to $P^{0.6}$ where P is the transmitted power [Ref. 11 : p. 1595]. Another theoretical relationship is that the number of meteor trails observed on a circuit is proportional to the square root of the transmitter power [Ref. 17 : p. 46]. The primary trade-off then is

transmitter power to system information throughput. MBC circuits currently in operation run transmitter power levels of 200 to over 1000 watts.

In addition to circuit throughput requirements, practical transmitter power considerations focus on the environment in which the transmitter will operate. MBC transmitters located in remote locations often have to depend on battery or alternative power sources, thus limiting transmitter output power. A mitigating factor for environments with limited power sources is the burst transmission nature of MBC. Generally, MBC transmitters operate with less than 12% duty cycles. This means that the power source need not provide, on a continuous basis, the large output levels required for high system throughputs. A test of a sea-going buoy MBC relay system was conducted by the Naval Ocean Systems Center (NOSC) during 1986 and 1987. This test successfully demonstrated the feasibility of maintaining a battery operated system at sea for extended periods of time. In this test, two 300 watt MBC stations were mounted in a deep ocean buoy. The stations were powered by zinc-air batteries. The buoy station was used to test the possibility of maintaining a MBC circuit between the West coast of the United States and Hawaii with the aid of relays. The batteries supported transmission cycles averaging 2 hours per day (8.3 % duty cycle) for over 7 months.[Ref. 18 : p. 80]

C. ANTENNA CONFIGURATION

Unlike transmitter power, there is an upper limit on antenna gains that Equations (II.1) and (II.2) do not suggest. Increasing antenna gains produces a corresponding decrease in antenna beamwidth. The increased power achieved through antenna gains is more than offset by the loss in observed common sky between transmitter and receiver. This means a loss in the number of mutually usable meteors.[Ref. 14 : p. 4]. In other words, the narrower the antenna beamwidth, the fewer meteor trails the antenna "sees." Beam widths below 10 degrees show no improvement in communications.[Ref. 17 : p. 46] The limit of functional antenna gain depends on the operating range of the circuit. For short range circuits (400-600 miles), 16 dBi is appropriate and 21-24 dBi for longer ranges (600-1200 miles) [Ref. 14 : p. 4]. For practical MBC circuits, horizontally polarized, yagi antennas have produced good service. Yagi antennas consisting of 3 to 10 elements can achieve 8 to 20 dBi of gain with half power beam widths of 20 to 40 degrees [Ref. 19 : p. 166-167].

An anomaly of MBC is that high-gain antennas for transmitting and receiving stations should not be pointed directly at each other, i.e.,not along midpoint of the great

circle path. A review of the geometry of MBC as shown in Figure 5 reveals that in order to be useful for communications, meteor trails at the path midpoint would have to be horizontal relative to the Earth. Few such horizontal trails exist; to produce them meteors would have to just graze the Earth's atmosphere. These geometrical conditions for reflection result in a practical communication null along the great circle path between transmitter and receiver. Better communications is achieved by offsetting antennas approximately 7 degrees to either side of the great circle path.[Ref. 17 : p. 42]

To understand this phenomenon the radiants of meteors must be considered. A meteor radiant is the area of the sky from which the meteor appears to fall. Given a uniform distribution of meteor radiants in the sky, the area from which the largest number of useful trails occur would be in two elliptically shaped regions lying to either side of the path midpoint and some what below the average height of the meteor trails [Ref. 20 : p. 1716]. These two areas are known as "hot spots" and are illustrated in Figure 12. The contours on Figure 12 plot the relative distribution of useful radiants. The ellipse labled 75 would be consider a hot spot. The second hot spot is obscured by the perspective of the figure.[Ref. 2 : p. 1649]

There are diurnal variations in the relative usefulness of these "hot spots." These variations are caused by the same factors as the diurnal changes in observed meteor activity, i.e. the concentration of meteor radiants towards the apex of the Earth's way [Ref. 20 : p. 1716]. For the northern latitudes, MBC circuits with east-west paths should have their antennas pointed towards the northern "hot spot" between 2400 and 1200. For the periods 1200 to 2400 the southern "hot spot" is more effective. For north-south paths the east side is better between 0600 and 1800, while the west side is better at night.[Ref. 20 : p. 1717] These relationships would be reversed for the southern latitudes.

The antenna polarization of choice is horizontal, i.e. the electrical field vector of the signal is parallel to the Earth's surface. In tests conducted at 46 MHz it was shown that horizontally polarized antennas out performed vertically polarized antennas by 3 dB. Cross polarized antennas, horizontal to vertical, perform significantly worse than antennas that share the same polarization, either vertical or horizontal.[Ref. 12 : p. 4-14] With vertically polarized antennas there is a short range null that occurs at 200 KM [Ref. 12 : p. 4-8]. This null is due to geometric factors, and suggests that, theoretically, no communications would take place between two vertically polarized MBC stations separated by 200 KM. Actual experience shows that several mitigating factors contribute to a substantial smoothing of the null. However, reduced communications

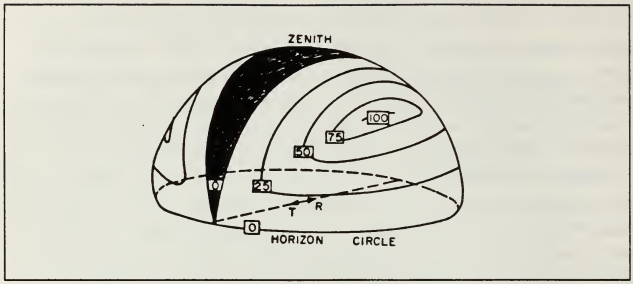


Figure 12. Distribution of Useful Radiants -"Hot Spots"

is experienced by vertically polarized stations on a 200 KM path. MBC circuits should be designed for horizontal polarization when ever possible. When vertical polarization is required, e.g. for mobile communications, all stations on the MBC network should be vertically polarized.

D. COMMUNICATION DISTANCE

The maximum limit on the distance covered by a MBC circuit using a single trail is a function of geometry. The heights where meteor trails form is 80-120 KM. This physically limits the ground-to-ground communication range to 2400 KM (1500 miles).[Ref. 13 : p. 1706]

There is some variance in the literature, on whether a minimum distance for MBC exists. Kokjer and Roberts report a communication dead zone at 400 KM [Ref. 21 : p. 23]. Other authors consider the effective range of MBC circuits to be from 0-2000 KM [Ref. 16 , 14]. The amount of common sky within the meteor region, that is seen by two stations, determins how effective a MBC circuit will be. Stations separated by more than 2400 KM share no common sky, and therefore, no communications is possible. At approximately 600 -700 KM separation, maximum volumes of common sky are obtained. As the distance between the two stations is reduced below 600 KM, the area of common sky that they see will shrink. Eventually, the volume of sky in the meteor region between the two stations is not enough to support MBC. However, as the amount of meteor trail propagation diminishes with reduced distances, other forms of

propagation come into play. At very close distances, line-of-sight (LOS) communications provides a continuous connection between the two stations. Beyond LOS, there are still communication opportunities offered by various atmospheric anomalies. Such conditions as forward scatter, ducting, and sporatic E-layering provide short-lived communication possibilities. As will be outlined in Section IV, the design of MBC systems allow maximum exploitation of any communication path opened between two stations, even for very short time durations. When LOS and the various forms of transient propagation are included, continuous communication coverage out to distances that will support meteor trail propagation can be achieved.

There is general consensus that the optimal distance for MBC link throughput is between 600 and 1000 KM. This is the distance that provides maximum common sky in the meteor region. The NOSC buoy test found continuous coverage for a MBC link from 0 to 860 nm over open water. This included 130 nm of what they considered line-of-sight (LOS) coverage. The NOSC study found the optimal communication distance to be at 600 nm.[Ref. 18 : p. 99-101]

The relationship between link throughput and range has been approximated from experimental data and is presented in Table 2. [Ref. 11 : p. 1595-1596].

Table 2. VARIATION OF THROUGHPUT WITH RANGE

Range (km)	Empirical relation for Throughput
200 to 480	$0.58T_o$
480 to 770	$(\frac{D}{770})T_o$
770 to 1280	T_o
1280 to 2000	$T_o[1 - 0.0006(D - 1280)]$

Note: D = range, T_o = Throughput at range-1000 KM.

These communication parameters define the basic capabilities and limitations of propagation by meteor trails. How MBC systems are designed to use these capabilities of the medium is the subject of Section IV.

IV. MBC SYSTEM DESIGN

A. BASIC SYSTEM CONFIGURATION

In order to develop an understanding of how MBC systems perform a basic system will be described. This system is shown as a block diagram in Figure 13. The system shown in Figure 13 is configured for full duplex operation. This means that two way, simultaneous communications can take place between both stations. Figure 13 illustrates a simple, point-to-point link; only two stations, Station A and Station B are shown.

As outlined in Section II, the nature of the meteor trail, propagation path requires MBC systems perform the following functions, to carry out communication:

- Detect when a path exists between the transmitter and receiver, and start the transmission of information by the transmitter;
- Transmit as much information through the path as possible when it exists; and
- Detect when the signal has faded to an unusable level and terminate the transmission when that level is reached.

Detect when path exists and start transmission. MBC systems distinguish between master stations and remote stations. In order to determine when a meteor trail, suitable for communications exists, one station transmits a "probe" signal. The probe can be transmitted continuously or on a set schedule. When the probe is heard, by the second station, with receive levels sufficient for error free reception, it informs the probing station that a suitable communication path now exists. The station that performs the probing function is considered the master station and the second station is the remote station. For the purpose of describing a basic system, Station A in Figure 13 has been designated the master and would transmit the probe signal on frequency #1. Station B is the remote; it would inform Station A on path conditions using frequency #2.

Figure 14 displays how a typical received signal would appear at the remote, receiving station. A simple way for the remote station to determine if the incoming signal has receive levels sufficient for error free reception is to set a fixed signal threshold. Such a threshold is shown in Figure 14. Signals received above this threshold will provide error free communications. When the received signal drops below the threshold, suitable communications are no longer possible.

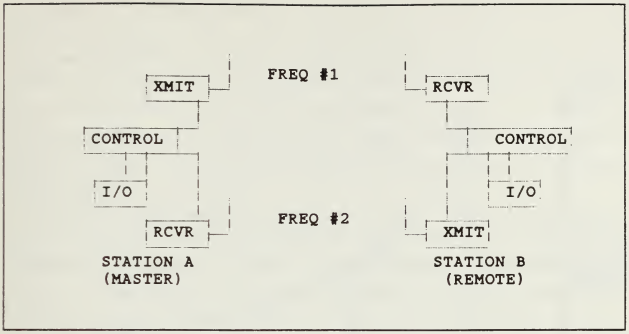


Figure 13. Basic MBC System Configuration

Transmit as much information through the path as possible. Once a communication path has been established, as much information as possible must be transmitted over the rapidly fading propagation path. This is the "burst" part of MBC. Many basic MBC systems use fixed transmission rates. With a fixed rate system, the transmission rate, (burst rate), must be set in relation to the system's receive threshold discussed above. Higher transmission rates require higher received signal levels to sustain them. The relationship among signal levels, transmission rates, and error free reception can be seen in Equations (IV.1), (IV.2), and (IV.3). A factor ρ is defined as:

$$\rho = \frac{E_b}{\eta_i} = \frac{\textit{bit energy (Joules)}}{\textit{one-sided, noise power density}\left(\frac{\textit{Watts}}{\textit{Hertz}}\right)} \qquad (IV.1)$$

Bit energy is related to received signal levels, P_r, and the time interval of one bit, T_b, by:

$$E_b = P_r T_b \qquad (IV.2)$$

The system's transmission rate would be the inverse of the bit interval or $\frac{1}{T_b}$. The relationship between ρ and the probability of a bit error, P_e can be expressed as:

$$P_e = Q(\sqrt{2\rho}) \qquad (IV.3)$$

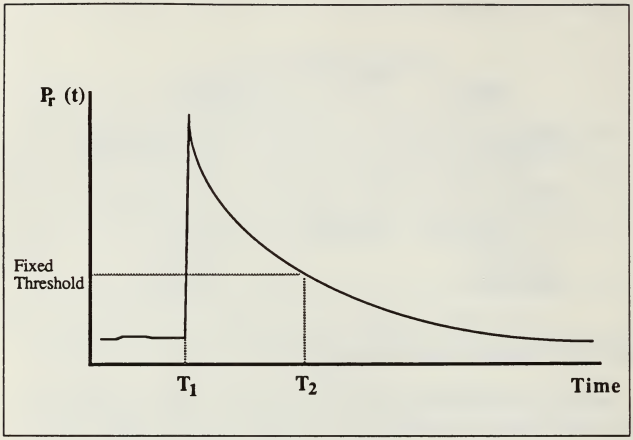


Figure 14. Received Signal with Fixed Decision Threshold

[Ref. 22 : p. 506] Where $Q(y)$ is a statistical operation to determine how much area on a Gaussian, probability density function occurs after the point y.

The probability of a bit error measures the amount of error free reception to be obtained from a MBC system. From the equations on the previous page, it can be seen that the probability of error, P_e, is inversely proportional to the received signal level, $\frac{1}{P_r}$, and directly proportional to the transmission rate, $\frac{1}{T_b}$.

Once a transmission rate is set for a MBC system, there will be a received threshold below which the probability of error becomes unacceptable. To set an optimal transmission rate for a MBC system, the acceptable amount of bit errors for the circuit must be considered in relation to the amount of time the received signal levels will be above a given threshold. In Figure 14, given the fixed threshold, the represented signal is only useful for the time period T_1 to T_2. For stronger signals this useful time period would be longer, and weaker signals would give shorter periods. The distribution of received signal levels is random and will change for different circuit configurations. The

same meteor trail parameters outlined in Sections II and III govern the distribution of signal levels on a given circuit. A critical MBC system design requirement is to find the right transmission rate for a given set of circuit parameters. The over-all information transfer rate would be the product of the transmission rate and the percentage of the time that the received signal is above the threshold level [Ref. 23 : p. 1694]. The percentage of the time that a signal is above the "usable" threshold is considered the duty cycle of the circuit. Duty cycle is one of the most important factors in the design of MBC systems [Ref. 13 : p. 1702].

Detect when path is unusable and terminate transmission. When the received signal level falls below the fixed threshold, useful communications are over. The receiving station must now signal the transmitting station to terminate data transmissions and return to probing operations. Signals received by meteor trails fade very rapidly. Signal fading rates as high as 500 dB/ sec can occur, however fades of 200 dB/ sec and less are more normal [Ref. 23 : p. 1695-1696]. To offset these high fade rates, the receive threshold must be set high enough to allow enough time for the transmitter to be notified and stop transmission. This extra time margin to stop the circuit reduces the duty cycle.

The steps that were outlined above are common to most MBC systems. They are basic to the establishment and control of communication paths over meteor trails. Actual systems may vary considerable from the basic configuration shown in Figure 14. The system may employ a single frequency; it could use a variable transmission rate, or it could involve several stations. Each configuration however, must address these basic steps in order to use the meteor trail path.

B. VARIATIONS ON BASIC SYSTEM

1. Communication Modes

The basic MBC system illustrated in Figure 13 is considered a full duplex system because it is capable of simultaneous, two way communications. In order to operate in the full duplex mode, the master and the remote station employ two frequencies. One frequency is used for transmission from the master to the remote; the other frequency is used from the remote to the master. Other modes of communication can also be employed.

Half duplex operation has been successfully employed on MBC systems [Ref. 23 : p. 33-53]. With half duplex operation the master and remote stations can not transmit simultaneously. Usually, a single frequency is used by both stations and they

must share it for alternate communications. To initiate communications with half duplex operation, the master station must intermittently suspend its probing signal to listen for the remote's response, indicating that a suitable meteor path has occurred. Once a link has been established, the process of stopping the flow of information is also more complicated. Data transmission must be periodically interrupted to see if the path still exists. If the meteor path has faded beyond the point of usability, the receiving station must wait until the next trail comes to tell the transmitting station how much of the message was received before communications were lost. Tests conducted aboard C-130 aircraft in the late 1970's found that half duplex operation reduced MBC system performance by less that ten percent for frequencies below 70 MHz. At higher frequencies, the reduction in performance, when compared to full duplex, rises rapidly to due the shorter trail durations.[Ref. 14 : p. 50]

Simplex or "broadcast" operation occurs when the information flow is one way only. The remote has no transmitting capabilities. The master station receives no feedback from the remote on when a meteor path has occurred or how much of the message was received. Because of this lack of feedback from the remote, broadcast operation requires a significant departure from the basic, MBC system model. With broadcast operation the master station must transmit messages compact enough to fit in the duration of an average meteor trail. The master must continue to send the same message until there is a high statistical probability that all remote stations have received the message. Figure 15 shows the transmission time required to ensure a 99% probability of reception by L remote units as a function of the total message time. The numbers listed in the figure are based on the average performance of the COMET system. On the average, the COMET system experienced a 0.58 second burst duration and an interval between bursts of 10 seconds.[Ref. 11 : p. 1593-1594]

2. Variable Transmission Rates

The basic MBC system presented above operates with a fixed transmission rate. Early MBC researchers understood that a fixed transmission rate was not the most efficient way to make use of a varying amplitude signal. More efficiency would be gained by transmitting information at the highest rate the received signal power could sustain, but this would require variable rate and variable bandwidth systems, unavailable at the time.[Ref. 23 : p. 1956]

Equations (IV.1) through (IV.3) illustrate this relationship. The probability of error is inversely proportional to the received signal level and directly proportional to the transmission rate. Holding the probability of error constant, high signal levels can

TOTAL MESSAGE DURATION	REQUIRED TRANSMISSION TIME (MINUTES)			
	L = 1	L = 10	L = 20	L = 30
35 ms	0.77	1.2	1.3	1.4
100 ms	0.86	1.3	1.4	1.6
300 ms	1.2	1.8	2.0	2.2
500 ms	1.7	2.6	2.8	3.2
700 ms	2.4	3.6	4.0	4.5
1.0 s	4.1	6.1	6.7	7.5
1.5 s	9.6	14.4	15.8	17.7
2.0 s	22.7	34.1	37.5	42.0

L = NUMBER OF REMOTE UNITS
AVERAGE BURST DURATION = 0.58 s
AVERAGE INTERVAL BETWEEN BURSTS = 10 s

Figure 15. Broadcast Message Requirements

sustain faster transmission rates then lower signal levels. As signal levels drop with the fading meteor trail, transmission rates must be reduced as well to maintain a constant probability of error.

In Figure 14, the portion of the signal above the fixed threshold (T_1 to T_2) represents signal levels that could sustain faster transmission rates than allowed by the basic fix rate, fixed threshold system. By following the fading signal with variable transmission rates more of the signal could be used for communications. Figure 16 shows how a variable rate system could adapt transmission rates to a fading signal. The sequence shown in Figure 16 occurs as follows:

- At 0.6 seconds the signal was recognized, and the system began to pass data at 8 kBPS;
- At 1.0 seconds the signal level was sufficient to sustain a transmission rate of 32 kBPS;
- At 1.16 seconds, the signal level dropped to support only a 16 kBPS rate;
- At 1.4 seconds, the level could support 8 kBPS;

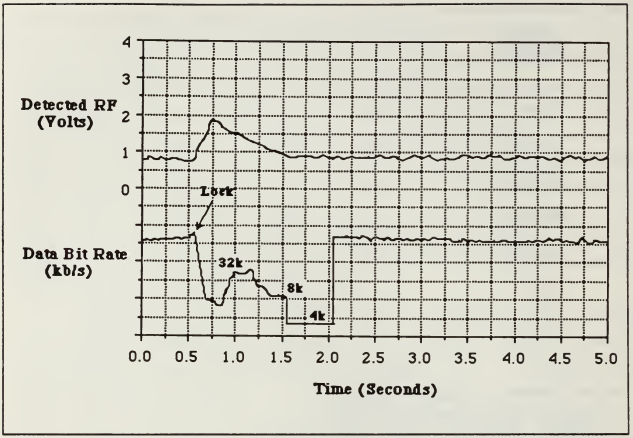


Figure 16. Variable Transmission Rate System

- At 1.55 seconds, the level continued to fall and only 4 kBPS could be sustained; and
- At 2.15 seconds, the receiver lost the signal and the system returned to a probe and listen mode.

[Ref. 24 : p. 56]

In order to achieve variable transmission rates in a MBC system, three conditions must be realized. First, the system receivers must have variable bandwidth filters and the transmitters must be capable of different transmission rates. Next, accurate and timely measurements of the received signal levels must be made. Third, a means must be available of telling the transmitter what rates can be supported by the receiver.[Ref. 25 : p. 0583] In a full duplex system, a path to provide this feedBack is available to the receiver. Variable rate systems are currently in operation with rates ranging from 2 to 64 kBPS. Increased data throughput of three to five times fix rate systems have been achieved.[Ref. 24 : p. 57]

3. MBC System Composition

The basic system presented in Figure 13 illustrates a simple, communication link between two stations. More than two stations can operate in a MBC system. MBC systems can be characterized as providing communications for:

- One station to one station;
- One station to many stations; and
- Many stations to many stations.

One station to one station links. These are the simplest form of composition. When just two stations form the network little consideration is needed for station addressing or coordination. Both full duplex and half duplex communication modes can be used for such simple point to point links.

A more complicated variation of this basic composition would be a relay system consisting of several point to point links. Figure 17 shows such a design. A relay system could be used to extend MBC beyond the normal range of 2000 KM. The links between each node are essentially like the basic system. To send a message from A to D would require three separate transmissions (A to B, B to C, and C to D). The message would be stored at each node and forwarded when a suitable meteor trail occurred.[Ref. 1 : p. 44-45] While this system would be a series of basic links, at least two of the nodes would have to assume the role of both master and remote, i.e. both probe and listen. An address plan would be required to identify each node and some form of contention resolution would be needed to determine what to do when two adjacent nodes tried to transmit simultaneously. Communication modes on a relay network require more coordination. In the system shown in Figure 17, half duplex operation could be used employing one frequency, but for the full duplex mode, frequency management would be necessary. A possible assignment would be:

- Station A transmit - frequency #1; Receive - frequency #2;
- Station B transmit - frequency #2; Receive - frequency #1;
- Station C transmit - frequency #1; Receive - frequency #2; and
- Station D transmit - frequency #2; Receive - frequency #1.

One station to many station compositions. Such networks have been used to connect a master station to a network of remote stations. These types of networks have been very successful in collecting small amounts of data from remotely located sensors. With this type of system the primary information flow would be from the remote sensor

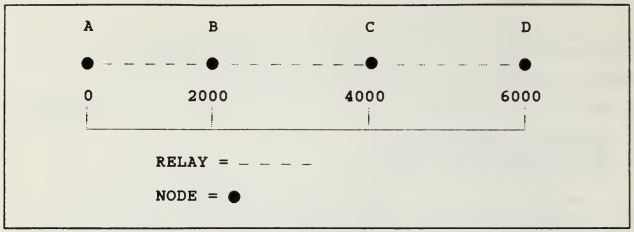


Figure 17. MBC Relay Network

to the master station. The master would be responsible for transmitting the probe signal. Individual sensors could be interrogated by including their address in the master's probe signal, or they could respond to the probe when they had information to report. The SNOTEL network is a good example of this type of MBC system. Data collection networks usually operate in the half duplex mode. High information throughput is not so critical for these systems and the extra expense required for two frequency operation makes the full duplex mode not cost effective.

Interconnecting many stations. This is the most complex form of MBC system composition. Early interconnected, MBC systems were similar to the one-to-many design of the sensor networks. A single network consisted of a master station and a collection of remotes. Instead of sensor data, the remotes sent text messages to the master station. The message traffic could stay with the master or be passed on to specified remotes. Modern MBC systems have evolved into sophisticated data networks, interconnecting many sets of masters and remotes. Such a system is pictured in Figure 18. MBC networking software, available "off the shelf" in 1987, was capable of interconnecting 15 master stations and 300 remotes [Ref. 24 : p. 60]. Such a network is based on the International Standards Organization (ISO) model of a layered communication system. MBC is considered a communication subsystem of the network, providing the physical, link, network, and transport layers. Following the ISO model, the selection of system frequency, modulation, and communication hardware comprise the physical layer of the network. The other layers, implemented by both hardware and software, are concerned with the following network issues:

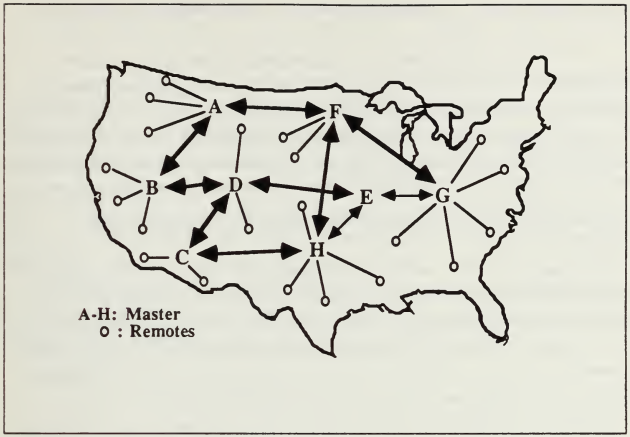


Figure 18. 1987 MBC Network

- The link layer deals with problems on the communication path between two MBC stations. Channel acquisition, contention algorithms, receive flow control, division of data into transmittable "packets", and error detection are the concerns of the link layer;
- The network layer is responsible for establishing a connection between two stations on the network. Messages flowing on this connection are usually relayed by intervening stations. Message precedence, packet accountability, routing functions, and connectivity management are the responsibilities of the network layer; and
- The transport layer serves as an interface between the higher layers that are concerned with message content and the lower layers that focus on message delivery. Message input flow control, message accountability, multiple destinations, and duplicate message filtering are in the domain of the transport layer.[Ref. 24 : p. 60, 26 : p. 213]

Most interconnected networks operate with two communication modes. Communications between master stations and their remotes employs half duplex operation. Master to master communications, which connects the various sub-networks together, is in the full duplex mode. This scheme facilitates frequency management. The

single frequencies used on the individual, master to remote networks can be reused on similar, non-adjacent networks.

As MBC networks increase in complexity, coordination problems are compounded. Modern, interconnected systems require much more detailed message formats and communication procedures than the basic MBC system. The many network issues listed above are a good indication of the complexity involved with large interconnected systems. The next sections on link and network protocols will consider some of the requirements for transfer of information on these types of MBC systems.

C. LINK PROTOCOLS - MESSAGE STRUCTURE AND INFORMATION CONTROL

The properties of the meteor trail communication path that are particularly important to link design include the random nature of trail occurrences, the brief duration of the communication path, the footprint's exclusion of contenting nodes, and the potential for the occurrence of nonmeteor trail propagation.[Ref. 12 : p. 4-101] MBC link protocols must accommodate each of these properties. Modern, MBC, text message networks require link protocols that provide the following capabilities:

- Transmission of continuous signals while probing and sending data. This ensures that all suitable meteor trails are exploited when they occur;
- While continuous transmission is necessary to provide maximum use of the randomly occurring meteor trails, transmission "time-outs" are also required;
  - Time-outs occur routinely when a station expends all of the data it has to transmit;
  - Half duplex operation, involves shutting off the transmitter and receiving for a given period of time, thus permitting reception of other transmitters;
  - Time-outs can be introduced into the system by deliberately stopping transmission if a node has been transmitting for longer than a specified time limit. This may be necessary under non-meteor propagation conditions to prevent two stations who are experiencing a continuous communication path, e.g., LOS or Sporadic-E layering, from monopolizing a network;
- Network configurations and modes of operation must include both master to remote and master to master communication options. Usually, master to master communications is done in the full duplex mode, while master to remote is half duplex;
- FeedBack procedures are used to establish link acquisition, link status, and to improve performance; and
- Data must be packaged into short segments to allow for the efficient transmission over single or multiple trails. Trail durations are short, typically lasting 50 milliseconds (ms) to 500 ms. Data packages must be sized to ensure their chances of being sent over a single trail. Long messages must be divided into several data

packages and transmitted over multiple meteor trails. This process is termed message "piecing." [Ref. 12 : p. 4-101 thru 4-111]

1. Message Piecing and Packet Structure

Most text messages sent over MBC systems are too long to be sent during a single meteor trail. In order to pass longer messages, the message must be divided into pieces, each piece short enough to be sent over a single trail. These message pieces are referred to as "packets". When long text messages are divided into separate packets, administrative information must be included in each packet to ensure proper delivery and to correctly reassemble the original message. Each packet, as a discrete communication unit, must also include bit sequences for synchronization, station identification, administrative control, and error correction.

Other data packets are required on MBC networks besides the text packets just described. These other types of packets are needed to control the various stages of the MBC exchange. MBC link protocols must address the following stages:

- Establish the link;
- Identify the connecting stations;
- Check for data availability;
- Exchange data;
- Conclude data exchange; and
- Probe for next link.

Each of these stages requires different functional information to be included in the data packets.[Ref. 12 : p. 109]

In a multi-staged network, data packets can be designed as either fixed or variable length. Fixed length packets would require that information fields be included for all possible functions whether used or not. A variable length packet would include only those data fields necessary to perform its assigned function. If the variable length option were chosen, the link protocol would include a separate packet type for each function. Both types of packet schemes have been used in MBC system design. Variable length packets have been shown to be more efficient for low to midsized networks and have been incorporated into a proposed Military Standard (MIL-STD-188-135) for MBC systems.[Ref. 27 : p. 10]

2. Error Detection and Correction

Error detection (ED) allows a station to determine if a data packet has been received without errors. Forward error correction (FEC) provides a station with enough information to correct errors in a received packet once they are detected. Both ED and FEC add considerable overhead to each data packet in the form of extra information bits. FEC requires significant overhead because the data packet must carry with it enough redundant bits to both identify errors and also correct them. The draft, MBC MIL-STD has found FEC too costly to implement for current MBC systems. FEC costs include, not only the expensive of equipment to implement the option, but also the reduced message throughput caused by enlarging the data packet.[Ref. 12 : p. 4-88] In lieu of FEC, the proposed MIL-STD uses ED with procedures for retransmission of faulty data packets.

The most common type of error that occurs when data is transmitted arise from short-lived noise impulses or other anomalies on the communication channel. These "error bursts" can cause a string of consecutive bits in a packet to be corrupted. An error burst begins and ends with an erroneous bit, although the bits in between may or may not be corrupted.[Ref. 26 : p. 98]

Polynomial codes provide a technique of ED that focuses on error bursts. This technique is named after the "generator polynomial" used to construct the code. The generator polynomial is a fixed number, defined by the link protocol and implemented into the hardware of the system. One standard generator polynomial is know as the American National Standards Institute (ANSI) CRC-16 code. The polynomial for ANSI CRC-16 is $g(x) = X^{16} + X^{15} + X^2 + 1$. Prior to transmission, each data packet is divided, modulo 2, by the generator polynomial. The results of this division is a set of binary, remainder terms which are added to the end of the data packet and are transmitted with it. These remainder terms are known as the "cyclic redundancy check" (CRC). The number of CRC bits produced by a code is a function of the largest exponent in the generator polynomial. For ANSI CRC-16, there are 16 additional bits added to the data packet for ED. On reception of the data packet, the receive station does another modulo 2 division on the entire data packet, both data and CRC bits. If the remainder terms of this division are all zero's, the packet has been receive uncorrupted. If there are one's in the remainder, than the packet contains an error and must be retransmitted.

When a corrupted data packet has been identified, the receiver must ask the transmitter for a retransmission. This process is known as "Automatic Repeat reQuest"

(ARQ). Several issues must be considered before an ARQ protocol can be defined. The first issue is whether the receive station will tell the transmitter about positive receptions or only the data packets received in error. If the receiver acknowledges (AKs) each correctly received packet, there is an increase in circuit confidence, but with a corresponding increase in overhead. With negative acknowledgment (NAK), the transmitter is only requested to repeat packets that were found in error.

There are three basic ARQ options: Stop-and-Wait (S&W), Go-Back-N (GBN), and Selective Repeat (SR).

Stop-and-Wait (S&W). ARQ techniques has the transmitter send one data packet and then wait for the receiver to return an AK if the packet was received correctly, or a NAK if it contains errors. S&W techniques are useful with remote sensor networks, where limited data packets are sent to the master station. If the master station positively acknowledges (AKs) reception of a data packet, the remote can discard it, thus freeing data storage space. This technique simplifies remote station hardware which may be critical for sensors operating in hostile environments.

Go-Back-N (GBN). With this technique, the transmitter sends packets continuously. When a corrupted packet is received, a NAK is generated by the receive station. On receipt of the NAK, the transmitter stops the data flow, goes back a "N" number of packets, and continues the transmission from that point. The "N" number of packets repeated is fixed for the system. It is based on the round trip delay from the receiver to the transmitter plus any processing delays that may occur. A correctly chosen "N" will ensure that the corrupted packet will be repeated, as well as, all subsequent packets. By fixing the number of packets to be repeated, the bookkeeping requirements at the receiver are reduced. Modified GBN procedure is a variation of this technique. With modified GBN, the NAK identifies the corrupted packets and the transmitter retransmits only the corrupted packet and the ones following it.

Selective Repeat (SR). This technique retransmits only those packets that are received with errors. The receiver's NAK must now properly identify the corrupted packets. Memory and bookkeeping requirements are increased to ensure packets are kept in order.

Both GBN and S&W, ARQ techniques have been used successfully in MBC systems. SR has a slight edge over modified GBN in throughput efficiency, while S&W is significantly slower. The ARQ techniques rank just the opposite for cost and bookkeeping requirements, S&W the lest and SR the most costly. The draft Defense Communications Agency (DCA) MIL-STD recommends a modified GBN approach for

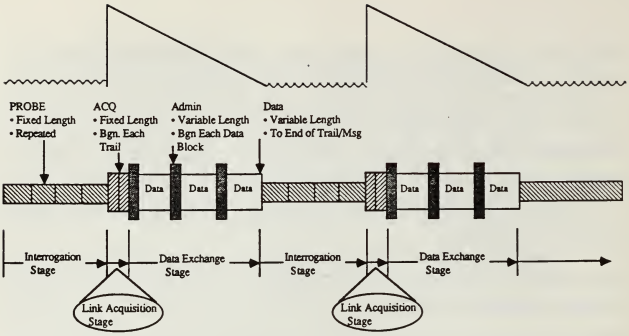


Figure 19. General Link Protocol Sequence

MBC systems that operate as data communication links and S&W ARQ for remote sensing systems.[Ref. 12 : p. 4-101]

3. Link Protocol Sequence and Link Control Frames

The link protocol can be divided in to three general stages:

- The interrogation stage, where the master station probes for meteor trails;
- The acquisition stage, where the remote station(s) respond to the master and a determination is made if either station will send data to the other; and
- The data exchange stage, where the actual data exchange occurs.

Two link sequences are shown in Figure 19 each with their corresponding meteor trail above them. To control the communication exchange, the link protocol must identify what types of information will be passed during each stage of the sequence. Such information must be explicitly specified in order to standardize the protocol and implement it in system hardware. Data communication protocols generally employ standardized, control packets or frames to initiate different link stages and to control information exchanges during those stages.

The DCA's proposed MBC, MIL-STD has defined eight control frames for communication links.[Ref. 27 : p. 10-14] The control frames are variable in length. Each control frame contains a number of fields depending on its function. Each field is one byte long. A byte is eight bits. All control frames include two fields of CRC-16 error

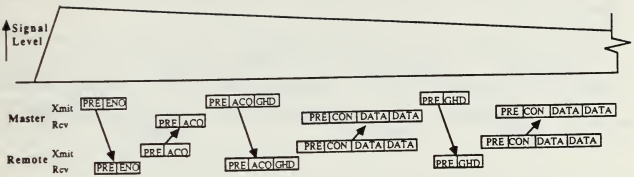


Figure 20. Half Duplex Acqusition and Data Exchange

detection code. In addition to control frames, the DCA MIL-STD uses a message data segment that contains 14 bytes of message data and 2 bytes of CRC-16 error detection code.

A half duplex link acquisition and data exchange sequence is shown in Figure 20. This sequence illustrates how the control frames and data segments would be used. The eight control frames function as follows:

- Preamble(PRE)Frame - The PRE frame is used to derive a reference signal and to provide bit and frame synchronization. The PRE is sent at the beginning of all new transmissions;
- Enquire(ENQ)Frame - The ENQ frame is transmitted by the probing master station. The ENQ is used to identify the probing master and to request selective responses to the probe. A probe is a sequence of a PRE followed be an ENQ;
- Acquire(ACQ)Frame - The ACQ frame is used by both the master and remote stations at the beginning of the link acquisition stage. The remote sends an ACQ to acknowledge the receipt of a probe and to attempt to establish communications with the probing station. The master sends an ACQ to acknowledge the receipt of the remotes ACQ. In either case, the ACQ will contain the last correctly received message segment that occurred on a previous meteor trail;
- Start of Message(SOM)Frame - The SOM frame is used to indicate that a station is going to begin sending a new message or a continuation of a message that was previously interrupted by a higher priority message. A SOM may also be used to interrupt a current message with a higher priority message;
- Go Ahead(GHD)frame - The GHD frame is used when a station does not have any (or any more) messages to send. The GHD frame also indicates the last correctly

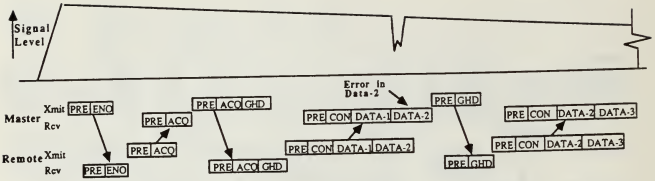


Figure 21. Half Duplex Negative Acknowledgment Procedure

received data segment. If this is not the last data segment sent, then the station receiving the GHD will treat it as a NAK. The GHD is only used in the half duplex mode;

- Continue(CON)Frame - The CON frame is used as a prefix to a set of transmitted data frames, if those data frames are a continuation of a message begun on the previous meteor trail;
- End-of-Data(END)Frame - The END frame is transmitted by a master station in the full duplex mode when it has no message data to send but is receiving message data from the master with which it is communicating; and
- Broadcast Control(BQX)Frame - The BQX frame is used to identify broadcast transmissions from the master station.

The half duplex sequence, pictured in Figure 20, shows an exchange where the remote has a message for the master but the master has no messages for the remote. If the master had messages for the remote, it would send message data segments instead of the GHD frame after reception of the remote's data segments. The presence of a CON frame in the remote's first data message segment indicates that a message that was started on a previous meteor trail is being continued. Otherwise, a SOM frame would be substituted for the first CON.

Figure 21 illustrates the procedure for negative acknowledgment. Again, the remote has a message for the master but the master has none for the remote. In this case an error has been detected in data segment two. The master station's GHD frame contains data segment one's identification code, indicating that it was the last correctly

received segment. On receipt of the GHD, the remote treats it like a NAK of data segment two and employing Go-Back-N (GBN) ARQ, it retransmits segment two.

D. NETWORK PROTOCOLS - ROUTING AND MESSAGE ASSEMBLY

The primary responsibility of the ISO network layer is the establishment and maintenance of a network wide connection between two higher level processes [Ref. 26 : p. 213]. The complexity of network layer protocol precludes a detailed investigation of the subject in this paper. Instead, a general summary of the basic network issues will be presented, followed by an example of how those issues are addressed by the DCA, MIL-STD for MBC.

1. Basic Network Issues

Network protocols provide dependable message transfers throughout the network. While link protocols are concerned with the single communications path between two stations, network protocols focus on how stations, separated by multiple links, can communicate over the network. Some of the basic issues that must be addressed include: type of switching, datagram or virtual circuits, network hierarchies, and flow control.

a. Type of switching

Circuit or packet switching can be used to route messages between communication nodes. Circuit switched networks provide a definite, physical path between two communicating subscribers for the duration of their connection. Telephone networks are good examples of circuit switching. Packet switched networks do not provide a physical connection through the network. With packet switched networks, subscriber messages are disassembled into individual packets, each packet contains the address of both the sending and receiving subscribers. The packets enter the network and are routed among Packet Switching Nodes (PSNs), until they arrive at the destination and can be reassembled into the original message. PSNs handle the packets on a "store and forward" basis; each packet is received and stored in a PSN's memory buffer before it is retransmitted to the next PSN. The nature of meteor trail propagation, necessitates packet switching for MBC systems.

b. Datagram or Virtual circuits

With datagram service, each packet is considered a self-contained entity with no relationship to other packets on the network. Each datagram contains a single message, including all addressing and control information necessary to ensure delivery to its destination. Datagram service could be used on MBC networks to pass

information from remote sensors or other "short message" sources. With virtual circuit service, several packets are usually required to send a message. When two stations communicate by sending a stream of packets over a network a virtual circuit is said to exist between them. While this virtual circuit is purely conceptual, it requires procedures to establish it and control information flowing over it.[Ref. 26 : p. 269].

c. Network hierarchy

Network hierarchies are concerned with how many levels of capability will be required in the system. In single level networks, all nodes have equal capabilities. All nodes must be capable of providing store-forward, message routing, and other network services. Single level networks provide flexible service for small systems, but produce switching complexities with larger, interconnected networks. Two-level networks allow routing and virtual circuit management functions to be centralized at individual network "hubs."[Ref. 12 : p. 4-185] Most modern MBC networks follow a two-level hierarchy like the one pictured in Figure 19. The local master station/remote station systems comprise the first level of the network, and the interconnected master stations form the second level. More than two levels of hierarchy are possible, but have yet to be developed for MBC systems.

d. Flow control

Flow control concerns the rate with which packets are transmitted over the network, ensuring that each PSN has sufficient buffer storage available to accept incoming packets. With a store-forward format, PSN buffer capacity can become over loaded. A PSN with a full buffer must tell adjacent PSNs not to pass any more packets until the ones it has are processed. This overload of storage capacity can propagate throughout the network unless mechanisms are in place to monitor and control the flow of information.

2. MBC Network Implementation

The DCA's Military Standard, (MIL-STD-188-135), outlines a proposed initial operating capability for MBC [Ref. 27]. The standard only allows for communication systems to be networked. Sensor systems are not address by the network protocol. The initial operating capability includes the following network specifications.

Hierarchy. The Mil-STD calls for a two level hierarchy. The first level would consist of local, star networks made up of a single master station controlling up to 255 remotes. Communications internal to the star networks would be over half duplex links. The second level would be formed by linking the master stations together. Master

station-to-master station communications would be in the full duplex mode. Master stations would be responsible for network routing and flow control.

Routing. The MIL-STD uses virtual circuit service with fixed routes. A network routing table is manually loaded into each master station when it is initialized into the network. The routing table catalogues all the other master stations in the network and how they are interconnected. Messages are routed on the basis of the shortest number of relays required to pass the message from the originating master station to the destination master station. Each relay is known as a "hop." Both remotes and master stations can originate messages. When a master station receives a message, the destination address is checked in the routing table and the "shortest hop" route is selected. The message is then forwarded on this shortest route. The next master station follows the same sequence until the message arrives at the destination master station and is passed to the intended remote. If there are two or more "shortest paths" from a particular master station, the message is sent on all the paths. Duplicate messages are killed by the receiving master stations.

Flow control. Flow control is accomplished by dividing messages into small segments for transmission. Once a message is entered into the network, its segments can be moved separately; intervening master stations do not have to wait for the message to be completely received before relaying it. The complete message is reassembled by the destination master station before it is sent to the intended remote station. Each master station maintains two main storage buffers, one for transmit, the other for receive. The buffers are divided into separate queues, one for each of the remotes and masters to which the station is connected. Each queue employs a set of logical pointers to manage message flow and maintain individual segments in the proper sequence. The MIL-STD has provisions for a message prioritization system. The protocol employs one byte of the address block to assign message priority. This would allow for 255 levels of priority if needed.[Ref. 12 : p. 4-183 thru 4-197]

E. MEASURING SYSTEM PERFORMANCE

Performance of MBC systems is measured by two basic criteria, message wait times and information throughput. Message wait time indicates how much time is required for a message, of specified length, to pass through the system. Information throughput measures the rate at which information flows through the system. Wait times and throughput are interrelated, but measure different aspects of system performance. Both

measurements are dependent on the MBC parameters outlined in earlier sections of this paper.

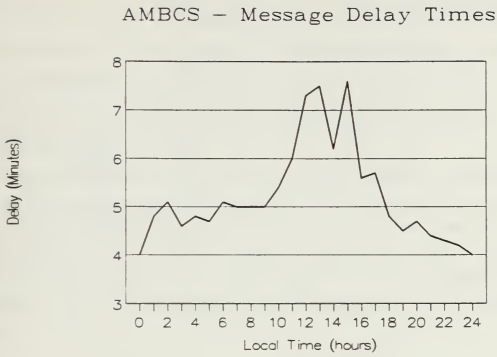
Figure 22 shows two views of message wait times. The first graph shows the average delay of message exchanges experienced on the Alaska Meteor Burst Communications System (AMBCS). Typical messages were 100 characters long. AMBCS spanned nominal distances of 1200 miles, using 300 watts of power, and 2000 BPS, PSK transmissions. The graph shows a distinct diurnal variation in wait times as would be expected from a MBC system.[Ref. 21 : p. 28] The second graph in Figure 22 shows message delivery times averaged for the month of February 1985. This data is from an USAF research link between Sondrestrom AB and Thule AB, in Greenland. The graph shows wait times in seconds, relative to transmission data rates in kBPS, for three separate operating frequencies. Again, the frequency difference in wait times is expected for a MBC system. The graph indicates that for each frequency there is a optimum transmission data rate that minimizes message wait times. As transmission, data rates increase, greater signal levels are required to support them, but meteor trail distributions capable of producing these high levels drop off rapidly as the required signal levels increase. Beyond a certain transmission rate, the wait time for a sufficiently long meteor trail exceeds the time required to send messages on more common meteors. [Ref. 15 : p. 3-14].

Information throughput is related to the duty cycle experienced by the particular MBC system. Duty cycle is the percentage of time that a propagation path exists. For a specific MBC link, duty cycle is a function of all the factors discussed in the earlier sections of this paper, e.g., time of day, time of year, physical separation of stations, frequency, transmitter power, etc. A simplified view of information throughput can be expressed as:

$$\textit{mean rate} = \textit{instantaneous rate} \times \textit{duty cycle} \qquad (IV.4)$$

[Ref. 28 : p. 1659] The mean rate is a simplified view of information throughput, in that, significant overhead may be included in the data sent over the system to control the MBC path. This data reduces the useful information throughput.

Figure 23 shows information throughput achieved by two MBC systems. The first graph displays results from the BLOSSOM system operated by the Royal Aircraft Establishment of the UK. The BLOSSOM system operated on a 813 KM link from northern Scotland to southern England in March 1987. The system transmitted 600



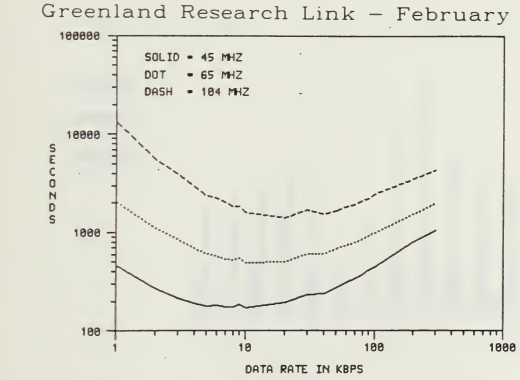
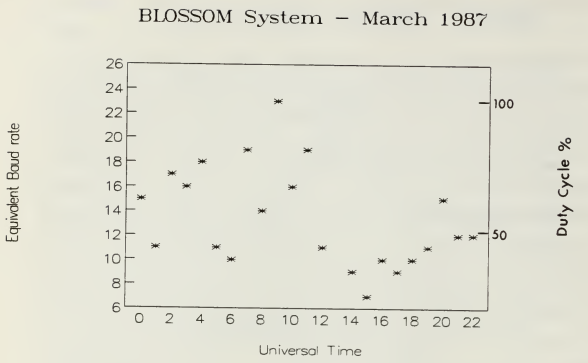


Figure 22. Measuring Message Wait Times



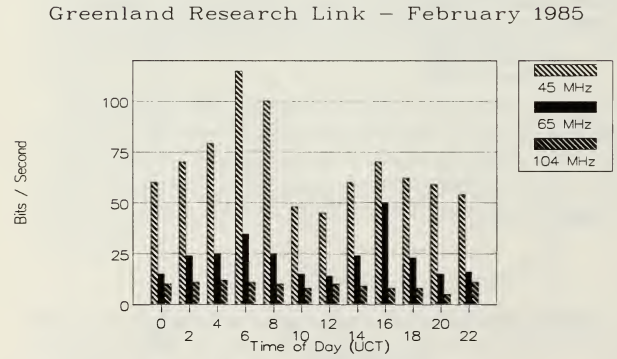


Figure 23. Average Information Throughput

watts on 46 MHz using antennas capable of covering both "hot spots." The BLOSSOM results shows both duty cycle and equivalent baud rate. At the point where 100% duty cycle was achieved, the throughput rate becomes the instantaneous transmission rate, i.e., 2400 Baud.[Ref. 29] The second graph comes from the USAF's research link in Greenland. This graph plots average throughput for the month of February in relation to the time of day. Again, a diurnal variation is present, and frequency dependency is also evident.[Ref. 15 : p. 3-12]

System performance will vary with the designs employed by each system. On a specific system, performance will vary with the time of day, the time of year, and where the system is geographically located. With any MBC system, however, wait times and throughput are the important criteria for evaluating performance. For moderately designed MBC systems, average message wait times of four minutes for 500 character messages, and average throughputs of 100 words per minute can be expected [Ref. 24 : p. 61].

V. MBC AND MARINE COMMUNICATIONS

This section will focus on how MBC can be applied to the tactical communications requirements of the United States Marine Corps (USMC). The section will begin with a general description of how the Marine Corps is organized for combat. Next, a set of general applications to tactical communications will be developed. These general, applications will use existing, operational systems as examples of what is currently possible with MBC. From this basis, specific Marine Corps applications will be explored.

A. USMC COMBAT ORGANIZATION

Marine Corps combat units fight in closely integrated teams of air and ground forces. These units are known as Marine air-ground task forces (MAGTFs). The MAGTFs are constituted for "force-in-readiness" missions requiring expeditionary forces for amphibious operations or operations ashore.[Ref. 30 : p. 6-1]

MAGTFs are formed in various sizes, tailored to the anticipated enemy threat. Regardless of size, all MAGTFs have a common organizational structure. MAGTFs are composed of the following elements:

- Command Element;
- Ground Combat Element (GCE);
- Air Combat Element (ACE); and
- Combat Service Support Element (CSSE).

There are three basic sized MAGTFs. This thesis will focus on the largest of them, the Marine Expeditionary Force (MEF). While the MEF is the largest MAGTF, many of the MBC applications to be developed could equally serve smaller Marine task forces. The general composition of the MEF is outlined below.

Command Element. The command element is responsible for the coordination of the other three elements of the MEF. While in overall command of the MEF, a "substantial portion" of the command staff's effort is focused on coordination with higher, adjacent, and supporting commands. Internal to the MEF, the emphasis is on direct liaison between subordinate element commanders, thus reducing the need for intensive oversight by the command element.[Ref. 30 : p. 6-2] The MEF commander is a major general or a lieutenant general. When the MEF conducts amphibious operations, the

command element serves as the landing force headquarters and the MEF commander becomes Commander of the Landing Force (CLF). A list of representative organizations that would be found in the command element include:

- MEF commander and staff;
- Communication battalion attachment;
- Air transportable communication unit (USN);
- Military police company attachment;
- Radio battalion attachment;
- Topographic company;
- Civil affairs group;
- Counterintelligence team(s); and
- Interrogation-translation team(s).

[Ref. 30 : p. 6-5]

Ground Combat Element The GCE of a MEF is normally a Marine division. The division is tasked organized and reinforced. Certain missions may require two divisions. When this occurs, the MAGTF commander's role in the direction and coordinations of ground maneuver is increased; the command element's organization must be augmented to meet this increased span-of-control. A Marine division averages 17,200 Marines and 850 Navy personnel. [Ref. 31 : p. 13] Some of the organizations that would be found in a MEF, GCE are:

- Marine division - three infantry regiments, one artillery regiment, one reconnaissance battalion, one combat engineer battalion;
- Light armored infantry battalion;
- Tank battalion;
- Assualt Amphibian battalion;
- Communication battalion detachment;
- Military police company;
- Special security communication team;
- Counterintelligence team(s);
- Interrogator-translation team(s);
- Dental company detachment;
- Hospital company detachment; and
- Radio battalion detachment.

[Ref. 30 : p. 6-6]

Air Combat Element. The ACE of a MEF is capable of self-sustained operations from expeditionary air fields. It provides all six functions of Marine aviation: offensive air support, antiair warfare, assault support, aerial reconnaissance, electronic warfare, and control of aircraft and missiles [Ref. 31 : p. 41-43]. The aviation combat element generally consists of one Marine aircraft wing. The commander of the aircraft wing is designated the Tactical Air Commander (TAC) for the MEF. Organizations found in the ACE of the MEF include:

- Marine aircraft wing - three fighter/attack aircraft groups, two helicopter aircraft groups, and one aircraft control group;
- Marine wing support group;
- Marine wing aerial refueler transport squadron;
- Marine wing tactical electronic warfare squadron;
- Marine wing tactical reconnaissance squadron;
- Low altitude air defense battalion;
- Light antiaircraft missile battalion;
- Radio battalion detachment; and
- Special security communications team.

[Ref. 30 : p. 6-6]

Combat Service Support Element. The CSSE is tailored to provide the MAGTF with combat service support that is beyond the organic capabilities of its subordinate elements. The force service support group provides this to MEF sized MAGTFs. Organizations normally found with this element include:

- Landing support battalion;
- Engineer battalion;
- Motor transport battalion;
- Medical battalion;
- Supply battalion;
- Maintenance battalion; and
- Dental battalion.

[Ref. 30 : p. 6-6]

As the largest of the MAGTFs, the MEF is organized for sustained, independent operations of an expeditionary nature. When deployed for tactical operations, the MEF

occupies considerable geographic area, and exserts influence on significantly more terrain. From the forward edge of the battle area (FEBA), where the forces of the GCE are engaged, to the rear areas where the CSSE's main supply dumps are staged, the MEF's area of operations covers several hundred miles. The ACE normally operates from advanced air bases, some of which could be located up to 300 miles away [Ref. 32 : p. 122]. The MEF also needs intelligence of enemy activity in areas far beyond the FEBA; this is generally coupled with the need to exploit that knowledge with long range air strikes. Often ground forces and artillery are used for raids, well into enemy territory. All of these factors create a need for long range communications.

The MEF's requirements for long range communications are significant. The long range communication capabilities of the MEF are always limited and often severely stressed. MBC represents a new means of long range communications that is not currently being used by the MEF. The remainder of this thesis will develop how MBC can be incorporated into the MEF's long range communication capability.

B. GENERAL APPLICATIONS FOR TACTICAL MBC

When developing applications for MBC systems, all other means of long range communications must be considered. In a tactical environment, long range communications can be considered, all communications using "beyond line-of-sight" (BLOS) propagation methods. The BLOS communication capabilities of the MEF include:

- Satellite radio systems - Both ultra high frequency (UHF) and super high frequency (SHF) satellite systems are organic to the MEF. UHF systems are more transportable, some are "backpack" transportable. SHF systems are capable of very high information throughputs but require larger equipment configurations;
- HF radio systems - The MEF has a large number of HF radio systems. Low powered HF radios can be found at almost every level of the organization. Higher powered systems are more limited and are usually employed at the element command echelons. For BLOS service, frequency availability is often critical. To maintain a BLOS, HF communication path between two stations, generally requires several frequency changes throughout a 24 hour period. Often, frequencies that are useable on a particular HF circuit are very scarce. For very, long range communications, HF radio systems may also require high power, transmitters and extensive antenna systems;
- Microwave radio systems - Microwave radios are organic to the MEF, located with both the ACE and the command element. The MEF command element maintains microwave links to its subordinate elements when the tactical scheme of maneuver permits. Microwave radio links provide large throughputs and flexibility, but require considerable planning before they can be installed. When used in an LOS mode, several links are required as relays to provide a BLOS circuit. Finding secure, high ground for these relays is often difficult. Microwave radios, operating

in the lower portions of the SHF frequency band, can use tropospheric scatter propagations to extend their communications to the BLOS range. Again, this propagation mode requires considerable planning and coordination between stations. Microwave radio provides point-to-point links, both points on the link must remain stationary for communications to exist. Its use for mobile operations is limited; and

- Cable - The cable assets of the MEF provide a limited, organic capability for BLOS communications. Commercial cable existing in the tactical operations area (TOA) could be put to service and is a significant resource when available. Cable, however, is vulnerable to enemy destruction and sabotage, representing a significant length of ground to protect. Long cable runs are not adaptable to mobile operations.

This inventory of BLOS capabilities is employed, by the MEF, to provide a mix of functional communication services. Text message traffic, voice telephone, and digital data networks are examples of these functional communication services. MBC is currently performing several of these functional applications for other organizations. Applications that could employ MBC are examined next.

1. Functional Applications

When compared to most of the current long range assets of the MEF, MBC is limited in both the throughput and waiting times required to disseminate information. MBC is not a means of high speed communications, nor is it suited for real time, voice exchanges. MBC messages may require substantial wait times, especially during unfavorable, diurnal, and seasonal periods. There are several areas of tactical communications, however, where speed of transmission and message wait times are not the critical service criteria. For some applications, availability, redundancy, or covertness may be more important communication considerations than throughput. Within its limitations, MBC may be capable of providing several of these communication services in a tactical environment.

Text messages. MBC is capable of providing a communication path for text messages. It can do this on single, point-to-point links or with networks connecting many stations. The AMBCS and the NORAD, 25th Air Division, networks are examples of the MBC text message capability. This type of functional application could be beneficial for low priority, administrative message traffic. MBC could be used as an overload circuit when long range, communication channels are clogged with high precedence message traffic. Often under conditions of high operational tempo, low priority, administrative traffic does not get through or is greatly delayed. MBC is a

method to increase communication capacity when additional satellite channels or useable HF frequencies are not available.

Text messages are often relatively short on tactical command circuits. Standardized formatting of messages, also helps to reduce their lengths. With MBC, shorter messages mean reduced waiting times. An MBC system with short, formatted messages could be useful as a backup to higher throughput systems that are vulnerable to enemy or environmental threats. The Alaska Air Command's, air control, MBC network is a good example of MBC backing up a "single strand" communication system.

Data messages. Data messages, in this context, are messages that are directly used by machines, instead of people. MBC by its nature is a data communication technique. It could be employed to send data messages that do not require "real time" reception. As an example of the "real time" requirement, a fire control, radar system needs very rapid updates of the position and range of its target. A long range radar may only require updates by the minute. The Alaska Air Command uses MBC on a long range, radar interception system. The U.S. Naval Electronics System Command tested the effectiveness of a MBC ship tracking system in June of 1979. The tests demonstrated "ship tracking is readily accomplished by meteor burst telemetry" [Ref. 33 : p. vii]. Waiting times ranged between 2.5 and 9 minutes for a 72 bit, ship's position message. Updating ship positions, on an every ten minute basis, could be more than adequate for such a relatively slow moving object.

Sensors. Tactical sensor systems are employed to provide intelligence on enemy activity and other environmental factors. Traffic movement on key avenues of approach is an example of information commonly delivered by sensors. Sensors are usually hidden in enemy territory by covert ground forces or dropped by aircraft. The range within which sensors can operate is often limited by the communication methods used by the systems. The SNOTEL network has demonstrated the effectiveness of MBC for controlling a large number of remotely located sensors. The operating distances of the SNOTEL system are comparable or greater than most tactical sensor systems.

Order wires. Order wire circuits are informal, communication channels dedicated to controlling specific functions. An example of an order wire circuit is a communication engineering circuit, used to control and coordinate all the other communication circuits linking an organization. Often these order wire circuits must "take up space" on the precious, BLOS communication path they are trying to control. When the BLOS path experiences an outage, the control circuit used to restore the outage is lost as well. MBC can be used to both, relieve the burden of providing channel

space for order wire purposes, and to provide an alternative means for engineering system restorals.

2. Environmental Applications

MBC has demonstrated advantages over other forms of communications when operated in certain "difficult" environments. These environments, often critical to the tactical scenario, pose severe challenges to conventional means of communications.

Nuclear environment. Extreme disruptions in communications can be expected during and after nuclear attack. There are strong possibilities that communication satellite systems will be degraded, if not destroyed. HF radio systems, depending on the ionosphere for BLOS communications, will also be vulnerable. Nuclear detonations can temporarily disrupt large portions of the ionosphere, causing HF blackouts that may interrupt communications for "hours or days" [Ref. 34 : p. 62]. MBC does not depend on the ionosphere as a propagation path. It is relatively immune to the ionospheric disturbances caused by nuclear detonations. MBC is "somewhat affected" by the increased D-layer absorption, that will occur in an nuclear environment, but it will "recover several hours before HF skywave" communications [Ref. 6 : p. 0569]. This robustness of MBC communications in a nuclear environment has lead several agencies to study its applications for trans- and post- attack, reconstitution efforts. The Federal Emergency Management Agency (FEMA) has established an experimental MBC network. A recent test on the FEMA network demonstrated, that MBC could be successfully conducted with buried antennas, thus enhancing system survivability.[Ref. 35 : p.552]

High latitude communications. High latitude in this context is poleward of 65 degrees latitude [Ref. 36 : p. 54]. Several factors contribute to reduced BLOS communications in the higher latitudes. Satellite communications at these latitudes is harder because of the difficulties acquiring a proper "look angle" to the equator. Most tactical communication satellites have geostationary orbits above the equator. At the higher latitudes, antennas must be aimed with angles very low to the horizon inorder to "see" these equatorial satellites. To achieve these low angles, antennas must often be placed on the highest available terrain. Usually, in tactical situations, the "highest available terrain" is inhospitable, difficult to operate from, or vulnerable to the enemy.

HF communications can be severely distressed at high latitudes. BLOS, HF communications is dependent on the ionosphere for a propagation path. In the higher latitudes, the ionosphere is often disrupted by auroral activity and polar cap absorption events. Auroral conditions serve to significantly reduce the range of frequencies that

will be useable over a given HF communication path and introduces temporal and spectral variations on the radio signals. While the number of frequencies are reduced, rapid frequency changes are required to adapt to fluctuating ionospheric conditions. Polar cap absorption can cause HF "black outs" lasting several days.[Ref. 36 : p. 52-54] MBC is much less affected by these conditions. Since it is not dependent on the ionosphere, MBC does not need to change frequencies to adapt to polar events. Operating at higher frequencies than HF, MBC is less effected by absorption. MBC can experience some auroral and absorption effects during severe polar disturbances but to a far less degree than HF. To cope with these conditions, MBC links must reduce transmission rates to the 100-300 BPS range, and use non-coherent forms of modulation such as frequency shift keying (FSK).[Ref. 37 : p. 6-2] These accommodations to distressed, arctic conditions represent reductions in performance, but MBC systems can continue to operate when outages lasting several days are experienced on HF systems.

The increased sporadic E-layering experienced at high latitudes can represent a dividend for MBC systems. Under sporadic E-layer conditions, MBC systems can experience a continuous, communication channel between several stations in the network. This will cause greatly increased throughputs and reduced wait times. Network protocols must be able to recognize this condition, however, and increase management functions, otherwise the individual stations contending for the channel will disrupt overall network efficiency.

Electronic warfare environment. As outlined in Section II of this thesis, MBC systems have small geographic "foot prints." Figure 11 illustrates how much information is available to an interceptor in the vicinity of a MBC station. MBC's low probability of intercept (LPI) and anti-jam characteristics, make it particularly suitable for several tactical applications. Covert units, operating in enemy territory would find the LPI aspects useful, as would, any organization that is vulnerable to indirect fire weapons. Resiliency to jamming is a communication quality that will be critical in high intensity conflicts. MBC provides a measure of anti-jam capability. As shown in Figure 11, to be 75% effective, an enemy ground jammer must be within 100 km of an MBC station. While this is not tactically unreasonable, such a jammer would be required to transmit a constant, wideband signal to be effective, making him an easily identifiable target for air and artillery. MBC is more vulnerable to airborne jamming, however, to seriously jam a MBC system from the air, the jammer would have to also forsake his own use of the lower, VHF radio spectrum.

C. SPECIFIC APPLICATIONS TO MEF COMMUNICATIONS

As was outlined in the beginning of this section, the BLOS communication requirements of the MEF are numerous. These requirements are increasing, as the combat possibilities facing the MEF evolve. The growing capability for over-the-horizon (OTH) amphibious assault, dramatically increase the BLOS communication needs. With OTH operations, all ship-to-shore communications are BLOS! The addition of the air cushion landing craft (LCAC), the MV-22 Osprey tilt-rotor assault aircraft, and the advanced assault amphibian vehicle to the MEF inventory, will greatly extend its tactical range. These three, new ship-to-shore vehicles will allow amphibious tasks forces to operate from distances significantly BLOS. The additional capability offered by MBC, could help satisfy the increased, BLOS requirements created by this new OTH amphibious potential.

Another recent trend, that has added to the MEF's BLOS requirements, is the threat to United States citizens in potentially hostile countries. Non-combatant evacuation operations (NEO), require the rapid projection of forces, often far from the base of operations. A common scenario, would have portions of the MEF, in an amphibious task force, steaming to a contingency area, when a threatened embassy requests immediate evacuation. A NEO under such terms poses an extreme challenge to all the MEF's assets, including communications. Operating from the limits of its reach, the MEF must project helicopter forces to the beleaguered embassy, and maintain them there until all personnel are evacuated. If possible, a forward arming and refueling point (FARP) will be positioned, half way to the embassy, giving the MEF more flexibility in its operations. This scenario requires an integrated package of mobile, BLOS communications. The package currently includes HF and satellite radio, and if possible, single channel, UHF radio, relayed by aircraft. MBC could provide an additional BLOS asset to the package. It could prove especially useful at the FARP, where LPI could be a critical element for success.

A final example of how MBC could support the MEF's evolving combat requirements is the growing concern with contingency missions in the northern latitudes. In the Atlantic, there is an increased awareness of the strategic importance of Norway to NATO's northern flank. In the Pacific, the Aleutians are seen as critical to U.S. security. Both areas could become future sites for MEF deployments. As previously discussed, these locations present severe challenges to satellite and HF radio communications, while MBC has several advantages to offer at these higher latitudes.

Thus far, the discussion has focused on MBC applications to the MEF as a whole. Useful MBC applications can be found within all elements of the MEF. Both, the command element and the ACE have several areas suitable for MBC. The GCE and the CSSE have more limited communication requirements that could benefit from MBC.

1. **Command Element**

The command element's scope of operations is larger in geographic area than any other element of the MEF. It is tasked with providing direction and coordination among the other three elements. Marine Corps doctrine calls for communications to be provided from the senior unit to the subordinate unit. Following this "senior to subordinate" stratagem, the command element employs the majority of its communication assets interconnecting the other elements of the MEF. This large geographic scope and inter-element responsibility, gives the command element an important role in the employment of MBC systems within the MEF.

The command element would be the logical organization to provide a MEF wide, MBC network. Cognizance of an inter-MEF network by the command element would provide several advantages:

- The command element has the doctrinal responsibility for inter-MEF communications;
- MBC systems require master stations which transmit a constant probe signal. A constant signal can represent a strong liability on the modern battlefield. The MEF command element will have other "high profile" emitters located in areas far back from the FEBA. This would be the place to operate MBC master stations. The other stations on the MBC network could be remote stations, which have significantly reduced electronic signatures; and
- Command element master stations, operating in the rear areas, would be far enough back to give remote stations, closer to the FEBA, the 100km, minimum distances required for effective MBC.

There are several functional services a MBC system could provide the MEF command element. If an inter-MEF, MBC system were established, the command element could find the following applications useful.

Text messages. The command element could use the MBC system to pass short, formatted messages to its subordinate elements. In this capacity, the MBC system would serve as an alternate to the MEF Tactical Net, or the MEF Command Net.

The Force Reconnaissance Company of the MEF would find the MBC system useful for passing short, text messages from locations deep behind enemy lines. The range, portability, and LPI characteristics of MBC, would be useful for this type of covert communications.

The MEF commander and his immediate staff may find MBC a useful way to maintain contact with the command element while airborne into the TOA. The range of MBC increases somewhat when airborne, but with a reduction in the LPI profile. Maintenance of the commander's communications while in transit to and from the TOA can often be a difficult communication task, and MBC could be useful in this role.

Order wire circuits. The command element maintains a MEF Communications Coordination Net, which "provides a means for the coordination, installation, and restoral of communication circuits"[Ref. 30 : p. E-9]. The "Comm Coord" is usually an HF radio net, providing communications to elements separate by up to several hundred miles of area. Often the useable, HF frequencies that will propagate over these distances are scarce. Under such conditions the "Comm Coord" net must compete for the frequencies with other MEF, HF requirements. Also, rapid frequency changes are necessary to maintain this circuit during the diurnal transitions at dawn and dusk. When communication personnel are focusing on the maintenance of their own circuits, command circuits suffer. MBC could prove very useful in the communication coordination function. Most messages passed over the "Comm Coord" net are very brief and could be easily formatted. Using a MBC system for this function, would release HF frequencies for other uses, and would give communication personnel a stable means of coordinating system restorals.

2. Ground Combat Element

The GCE of the MEF has more limited BLOS, communication needs. There are some however, that are suitable for MBC. The GCE operates close to the FEBA and does not often develop the distances necessary for effective MBC, among its subordinate units. Employing a MEF wide MBC system, with the master stations operating far back, in rear areas, would increase the utility of MBC to the GCE. When the GCE command element is too close to the MEF for MBC, alternate means of communications could be used to pass the MBC messages, received by the master stations, up to the GCE. There are several GCE missions that could employ MBC.

Text messages. There are two GCE units that could make use of MBC for their BLOS message needs. The first is the Division Reconnaissance Battalion. The Reconnaissance Battalion can field 48, four-man, scout teams [Ref. 31 : p. 25]. These

scout teams will range beyond the FEBA, conducting ground reconnaissance and surveillance of enemy activity. The scout teams accomplish their mission through "stealth, maneuver, and rapid reporting" [Ref. 31 : p. 25]. MBC systems could easily facilitate the stealth and maneuver aspects of the mission. The rapid reporting requirement would need to be analyzed to determine what wait times are acceptable to the situation. A worst case scenario, would have a message wait time of 10 minutes for a 100 character message. This would be received at the MEF master station in the rear. If the master station entered the message into a fast digital network, such as a tactical packet radio network, the additional time required to pass the message forward to the division would be nominal.

A second use of text messages over a MBC system, would be for the Light Armored Infantry Battalion (LAIB). The LAIB uses very fast, but "thin skinned," light armored vehicles (LAV) to conduct security, reconnaissance, and limited offensive defensive operations, 15-100 KM forward of the FEBA.[Ref. 38 : p. 61] Acting as a "screening force" for the GCE, the LAIB, depends on speed of mobility and stealth for protection from enemy anti-armor weapons [Ref. 39 : p. 49-50]. MBC could provide a LPI, BLOS path for the LAIB. The command and control (C^2) LAV variant, could be fitted with MBC equipment and be positioned to facilitate both, LOS communications to the LAVs on the screen, and MBC to the MEF, master station operating in the rear. Again, an alternate means of communications would pass the message from the master, up to the GCE. The C^2, LAV variant must be stationary while transmitting the MBC message, but this requirement is similar to most BLOS methods.

Sensors. The Sensor Control and Management Platoon (SCAMP), attached to the Marine division, provides the MEF with radio-linked, unattended ground sensors [Ref. 40 : p. 28]. These sensors are used to track enemy activity and can report seismic, magnetic, infrared, and audio data via an LOS radio. Radio relay equipment is required to extend the sensors range; 50 miles is considered the nominal range for these sensors [Ref. 41 : p. 31]. The sensors can be hand emplaced or dropped from aircraft. MBC has a proven record of passing sensor information. With MBC, the sensor's range could be dramatically extended, reducing the need for relay equipment except for short range applications.

3. Air Combat Element

The command and control organization of the ACE is known as the Marine Air Command and Control System (MACCS). For MEF sized ACEs, the MACCS is mostly automated, capable of real time, information sharing over large geographic areas.

The non-automated portions of the MACCS, require voice and text message communications over equally large areas. The MACCS's geographic scope encompasses, air control agencies, moving with the GCE, to advanced air fields operating up to 300 miles from the TOA. The ACE commander and his staff will be located at the Tactical Air Command Center (TACC). The TACC will normally be located at an airfield within the TOA, but far enough back from the FEBA to be defendable without maneuver. The TACC offers a good location for a second master station in a MEF, MBC network. Being located close to an airfield, and requiring high powered "emitters" for its other communications, the TACC can afford to host an MBC master station transmitting a constant probe signal. An extra master station would also give a inter-MEF, MBC system increased redundancy. Some functional, MBC applications that could be used by the ACE are listed below.

Text messages. One of the highest priority messages that the ACE produces is the daily, air fragmentary order. The "air frag" details all the scheduled flights that the ACE will fly on a given day. The message is voluminous, and takes considerable effort to disseminate to all elements of the MEF. The "air frag" is not a good candidate for MBC. Under ideal conditions, all available high speed communications, are necessary to "pass the frag." Often helicopter couriers are needed to get it out on time. After the "air frag" has been passed however, a large percentage of the ACE's communications involves reporting on the progress of the "air frag's" execution or making small modifications to it. Often, these types of communications use short, formatted messages, ideal for MBC. Generally, the messages sent to administer the current "air frag", can afford the several minutes of wait time, required by MBC. If a MBC system was used to pass these types of messages, the high speed circuits would be more available for time sensitive messages or the ones requiring larger throughputs.

Data circuits. As part of its air control function, the ACE deploys a system of radar sites interconnected by data circuits. This system is used to maintain a common picture of the air battle among all control organizations within the MACCS. One of the systems used to share this radar data, is know as the Tactical Digital Information Link A (TADIL A); in the Navy it is also called Link 11. TADIL A uses single channel radio, in a time shared, network configuration to maintain the common air picture. For long range applications TADIL A uses HF, while UHF is employed for shorter ranges. As with the USAF's Alaska Air Command, MBC could have a limited TADIL A role. An MBC system's usefulness for TADIL A type circuits would be limited to, scenarios that do not need large data throughput or, have longer wait time requirements. Air

sectors, cluttered with aircraft, demand systems with large data throughputs in order to update the many "tracks" that will appear on the radar screen. Air sectors with limited air activity, do not need data systems with large throughputs. Wait time requirements are also relative to the tactical application. The time required to pass data is critical for short range, antiair systems such as surface to air missiles. For long range intercepts, with high performance aircraft, wait times of several minutes may be acceptable for the initial vectoring of the aircraft. When the interceptor aircraft close with their targets, systems onboard the aircraft could provide more rapid radar tracking. In scenarios that are not so appropriate for MBC, it may still be beneficial if the other alternatives are limited. MBC might be the only alternative in some high latitude or nuclear environments or for "single strand" communication situations. In such cases, a MBC system operating as an overload or backup path could provide critical redundancy for air control.

4. Combat Service Support Element

The CSSE for the MEF, is the Force Service Support Group (FSSG). Units from the FSSG will be found supporting all elements of the MEF. The CSSE is responsible for the movement of supplies from the main points of entry into the TOA, ensuring timely delivery to where ever they are needed. Points of entry include beaches, ports, railheads, or airfields. In combat, the FSSG uses two types of distribution schemes to provide service and support. With supply point distribution, the units being supported come to the supply point to receive supplies and service. With unit distribution, a detachment from the FSSG brings the needed supplies and services to the unit receiving the support. In MEF sized operations, the supply points operated by the FSSG can range from large, sprawling complexes located in the rear areas, to small, well camouflaged, bivouacs close to the FEBA. Unit distribution is conducted by mobile, Combat Service Support Detachments (CSSDs), that move with the units being supported.

This system of combat service support, has several impacts on the communication needs of the CSSE. First, the area that must be covered with communications is large, basically encompassing the entire MEF TOA. Secondly, the volumes of communication traffic passed within the CSSE vary greatly by unit size and the distribution method used for support. Rear area supply dumps, often send and receive bulky, formatted messages used to maintain large data bases. The high volume, automatic data processing (ADP) assets of the MEF will be located with the CSSE, in these rear areas. Mobile CSSDs, providing pre-programed, blocks of supplies and

services to specific units, send and receive short, formatted messages reporting exceptions from the pre-planned flow of supplies. Often these units spend a large portion of the night on the move, trailing their supported unit. During day light, the CSSD rely on camouflage and reduced activity to hide their presence from the enemy.

MBC's potential role in communications for the CSSE is limited. The bulk of the CSSE communications requires large throughputs. Physical means of communications, e.g., courier delivery of data tapes and long messages, is often a more practical alternative to MBC when high speed electronic circuits are unavailable. There are several areas, however, where MBC and the CSSE could be mutually supporting. The CSSE rear areas would provide good locations for MBC master stations. Like the large airfields of the ACE, some of the large supply depots operated by the CSSE will be staged far enough back from the FEBA to achieve the operating distances necessary for MBC. Also, a constantly probing transmitter will not significantly degrade the security of these large, active operations. MBC can also provide the CSSE with several communication opportunities.

Text messages. The mobile CSSDs operate very close to the FEBA, relying on cover and concealment as protection from the enemy. As discussed above, these units carry pre-programed blocks of supplies for the units they support. The CSSD needs a BLOS, communication connection back to the rear area supply points to schedule and coordinate resupply. Because most replenishment received by the CSSD comes in preplanned supply blocks, the communication messages can be limited to reporting exceptions to the plan. MBC could be useful in this environment, providing a LPI means of passing short, formatted messages.

Military Sealift Command. The Military Sealift Command (MSC) provides the merchant ships that are used to carry supplies into the MEF TOA. During amphibious operations, MSC shipping is used for the assault follow on echelon, which loiters outside the TOA until the beach is securely established and capable of off loading their cargos. Communications with the assault follow on echelon is not strictly a MEF responsibility, but the coordination and scheduling of the echelon's activities is so critical to the MEF, that CSSE liaison teams are often embarked aboard the MSC ships. Communications aboard the MSC ships, that can interface with the MEF are very limited. MBC could provide a means of supporting the CSSE liaison teams aboard the ships. A mobile, MBC communication package carried with the liaison team, would take up a small amount of space and would provide LPI, BLOS communications appropriate for this mission.

5. Summary of MBC Applications

The previous discussion has identified potential applications for MBC within all elements of the MEF. MBC is most appropriate for communication situations where environmental considerations are more important than system throughput or wait times. Environmental considerations include nuclear, covertness, or operations at high latitudes. In this context, the availability of substitute means of communications could be considered an environmental issue.

Effective application of MBC, in the MEF, requires certain accommodations to MBC's inherent limitations. To achieve the distances necessary for efficient meteor trail propagation, the MBC master stations would need to be operated far to the rear, in the MEF TOA. This would be a logical location for a constant emitter, but it assumes that a higher speed, message system would be available to relay the MBC messages to their intended recipients. Such a system may, or may not, be available. Another accommodation for MBC, is the assumption that message traffic could be reduced to small formatted messages. While many tactical situations would allow for such formatting, there is often a reluctance on the part of message drafters to use message formats. Operations codes have been used successfully by USMC units for many years, but the hesitation to adopt the Joint Interoperability of Tactical Command and Control Systems (JINTACCS) message formats is an example of the pit falls associated with the introduction of new message formats.

The MBC applications discussed above, postulated a single, inter-MEF, MBC system which would provide various communication functions to different MEF elements. The time division multiple access (TDMA), provided by the physics of meteor trail propagation makes this possible. To a point, the more geographically disbursed stations that are operating on a MBC system, the more efficient it is in terms of the total communications being provided. Such a system is a departure from how communications is traditionally structured in USMC organizations. Doctrinally, communications follows command authority. USMC communication systems are organized along the "chain of command." Lateral communications go up to a common superior, across, and then back down the chain of command. Functional communications, interconnecting several different units, e.g., fire support, are often centralized in formal, organizational structures, e.g., Fire Support Coordination Center (FSCC), which employs elaborately documented procedures to define unit relationships and responsibilites. An inter-MEF MBC system, providing communications for all MEF elements, and to all organizational levels, would require significant changes in

communication philosophy. Such changes could create problems not immediately apparent.

The final section of this thesis will evaluate the overall advantages and disadvantages of MBC to the MEF. The applications with the greatest potential will be identified. The thesis will conclude with recommendations of areas needing further study.

VI. CONCLUSIONS

MBC is a mature technology which is successfully filling the communication needs of several organizations. This thesis has focused on the application of MBC techniques to MEF communications. To do this, both the theory of meteor trail propagation, and the design criteria, necessary to use this means of propagation was explored. The application of MBC to the MEF was next developed, using general communication concepts, environmental applications, and specific MEF communication examples. The analysis highlighted several strengths and weaknesses that MBC brings to tactical situations. These advantages and disadvantages will be outline below.

A. ADVANTAGES AND DISADVANTAGES OF MBC

The use of MBC by the MEF offers advantages, as well as, several disadvantages. Most communication systems present the same sort of tradeoffs between benefits and costs. To evaluate MBC, it must be compared to alternative means of BLOS communications available to the MEF.

1. Advantages

The communication advantages that MBC bring to the MEF are discussed below.

Inexpensive. As a radio medium, MBC is significantly cheaper than terrestrial means of BLOS communications, e.g., microwave and cable. It does not require the expensive satellite and ground station facilities, that satellite systems depend on. Current off-the-shelf, commercial MBC equipment can run $2K and up for sensor remotes, $15K-$30K for text capable remotes, and $150K-$250K for variable rate master stations. These prices are for the basic transmitter/receiver/controller units. Antenna systems, power supplies, and environmental casing would be necessary to adapt the basic units to tactical applications. The total price of tactical MBC units would be comparable to most military HF radio systems. Compared to the high powered, shelterized HF units, MBC systems could be cheaper because of less elaborate antenna systems needed for meteor propagation.

Simple to operate. MBC is basically a "hands free" system. Except for inputting messages, MBC operators have minimal operational duties once the MBC system is installed. Satellite and terrestrial systems share this advantage, but BLOS, HF radio

circuits require experienced operators to monitor the channel and shift frequencies as the propagation conditions change.

LPI and jam resistance. MBC provides a measure of covertness and anti-jam capability. The random nature of the propagation path, and the burst method used to communicate over it, makes meteor burst transmissions difficult to detect and intercept. To jam a MBC system, the jammer must be very close to either the transmitter or receiver, sharing the same geometry relative to the meteor trails used for propagation. This requirement makes the jammer very vulnerable to offensive actions. Both satellites and HF radios have weaknesses in electronic warfare situations. Satellite systems offer some LPI to ground, communication stations, but are very vulnerable to a jammer that attacks the satellite. HF radio signals, can propagate for long distances, but are ripe targets for enemy detection and interception. HF ground stations can be effectively jammed by "stand off" jammers, operating far from the offensive range of tactical weapon systems.

Stressed environments. MBC has distinct advantages over HF and satellite radio systems in the stressed, communication conditions present at high latitudes or in nuclear environments.

Extra asset. MBC would represent a new means of BLOS communications for the MEF. As an addition to the BLOS inventory, MBC can help increase the BLOS communication capacity of the MEF, and provide a redundant path where only "single strand" communications operated previously.

2. Disadvantages

MBC has some distinct problems as a BLOS communication resource relative to its application to MEF communications. Some of the disadvantages that have been identified are listed below.

Limited throughput. MBC systems are slow, compared to the alternative BLOS means. HF radio systems in the MEF are currently operating at 300 BPS and a few of the larger systems are capable of 1200 BPS data rates. Satellite and terrestrial, BLOS systems operate in excess of 2400 BPS. Current MBC systems deliver 100 WPM under the best conditions.

Wait times. The nature of the propagation path requires MBC systems to wait until conditions are correct before transmission can begin. The alternative, BLOS systems operate at the "speed of light." The only waiting required, by message recipients, involves the administrative processing of the message. MBC messages would require the same administrative processing, but impose additional wait times on message

delivery. Average wait times of four minutes can be expected for a 500 character message.

Limited spectrum. Effective MBC operates over a narrow range of frequencies in the lower VHF band. Spectrum in this band is very crowded, both with commercial and military applications. Large scale employment of MBC by the MEF would be hampered by the lack of available frequencies. Frequency availability is a significant consideration for HF, BLOS communications, but is less significant for the satellite and microwave alternatives.

Distance requirements. MBC has little trouble providing the maximum operating distances required by the MEF. The problem is that, MBC needs a minimum stand off distance between two communicating stations to achieve the areas of common sky necessary for effective meteor trail propagation. There is some indication that MBC systems can compensate for this minimum distance requirement by exploiting other transient, propagation opportunities. To accommodate this minimum distance requirement, a MEF, MBC system would need to locate its master stations in rear areas and, in some cases, use a higher speed, inter-MEF communication system to relay the messages to their intended recipients. This requirement is not shared by the other BLOS, alternatives, as a function of the communication medium. While HF radio has some trouble covering terrain between ground wave and "comfortable," skywave propagation ranges, the 50-150 mile, first, skip zone can be covered with near-vertical-incidence techniques. Satellite radios and terrestrial alternatives do not have minimum distance problems. The need to have one organization receipt for messages, destined for another organization, and then retransmit the message using an alternative communication path, is a common way to distribute traffic received from sources outside the MEF. This process of "guarding" for message traffic is a function of organization not of the communication medium, yet it is a standard way of providing MEF elements with connections to national communication systems. The minimum distance requirement of MBC would require a similar method of message delivery.

3. Potential Benefits

Like all communication systems, MBC requires trade offs between advantages and disadvantages. The greatest apparent benefit of MBC, is that it represents an additional, BLOS capability that can both supplement and compliment existing MEF communications. It can supplement overloaded circuits by both, providing an extra channel to pass, certain, back-logged traffic, and acting as a back-up circuit to "single

strand" communication paths. As a compliment to existing MEF communications, MBC can offer a "slow but steady" method of passing messages under hostile conditions.

MBC is not a panacea, it will not solve the many BLOS, communication challenges facing the MEF. It has significant weakness. As the growth of technology is pushing communication systems to increasingly higher data throughputs, MBC systems are offering almost primitive, data capacities. What MBC does offer is very modest, redundant protection for "single strand" circuits, and the ability to get some information out of a hostile environment when no other communication method will work. For the combat situations facing the MEF, what MBC offers is attractive.

B. AREAS FOR CONTINUED RESEARCH

While MBC is a mature technology, very few manufacturers offer operational systems, and comparably modest research is being conducted on MBC techniques. Areas for further research holding the greatest potential, relative to MEF applications, fall into two basic categories: technical research and research relative to MBC operations in tactical environments.

- Technical research - Adaptable data rate systems, capable of following the fading meteor burst channel, offer the greatest potential for increasing system throughputs. Message coding and protocols, that increase MBC network efficiencies, hold the best promise for reduction of message wait times.
- Operational research - The ability of MBC systems to operate at close-in ranges (0-100 miles), needs more work before tactical applications can be properly planned. Light weight, man-packable units and power sources need to be developed, allowing MBC to be integrated into the ground combat arena.

The early growth of MBC was stunted in the mid 1960's by the development of satellite communication systems. With the growing awareness of the limitations of satellite systems, particularly under tactical conditions, interest in MBC has increased. As MBC systems become more operationally acceptable, technological improvements to current system weaknesses will be developed. It is important for tactical communication personnel to monitor this progress, and exploit the communication benefits MBC has to offer.

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